TRANSFORMABLE BUILDING STRUCTURES

Design for disassembly as a way to introduce sustainable engineering to building design & construction

Proefschrift

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aan de Technische Universiteit Delft,
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in het openbaar te verdedigen
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Introduction

"Time, is a three-fold present: the present as we experience it, past as a present memory, and a future as a present expectation. (Kant) By that criterion, the world of the year 2025 has already arrived, for in the decisions we make now, in the way we design our environment and thus sketch the lines of constraints, the future is committed." (Dutt 1996)

A Research background and a problem definition

Observers of current and future trends predict that the 21st century is the beginning of an era that will be defined by temporary, multi-functional, and virtual organisations. The nature of working and living will change drastically such that society will require completely new types of structures. Besides the dynamic changes within society, another factor that indicates the need for an alternative way of building is the pattern of use of natural resources within the construction industry — a pattern which has proven to be unsustainable. Recent estimates indicate that existing buildings account for 2/5 of the world's annual energy use, one sixth of its water consumption, and one half of its waste stream. The World Resource Institute projects a 300% rise in energy and material use as world population and economic activity increases over the next fifty years. The physical impact of an increasing building mass in the industrialised and developing world becomes undeniable in the 21st century.

A number of studies have warned that demolition processes account largely for the negative environmental impact of buildings. The main problem lies in the fact that the assembled materials have no potential for recovery. Consequently, existing construction methods use only a small percentage of the durability potential of building materials. This percentage tends to decrease as material use shortens. Generally, there is a disproportion between the use and the technical life cycle of building materials. This disproportion tears building structures apart and is responsible for the negative environmental impact of building assemblies. In other words, the combination of current building methods and market activities, which result in shorter phases for use of buildings, systems, and components, is a bottleneck for the decrease of waste streams and material and energy use within building construction. Exhaustion of raw materials and energy is forcing governments, developers, architects, and the building industry to reconsider current ways of building.

The objectives method and research domain

The main question of sustainable building is how to find a balance between the increasing dynamics of change, which is related to the increased resources

consumption, and the key principles of sustainable engineering (such as; conceiving
natural resources, saving energy, reducing waste, etc). Many studies have recognised that this can be achieved by extending the life cycle of buildings and their materials.

One long-standing conviction held by many is that buildings last longer when made of more durable materials. However, everyday demolition practice that results in material and energy losses proves that:
1. due to the frequent functional changes the ‘use life cycle’ of materials is often shorter than the ‘technical life cycle’ of materials;
2. materials are often integrated into a fixed assembly; the replaceability of one element means the demolition of others;
3. the end of the life cycle of buildings is associated with demolition and waste generation.

Bearing this in mind, one can say that a key element of extending the life cycle of buildings and their materials involves designing the ability to transform all levels of technical composition by means of disassembly and reconfiguration, regardless of the materials used. To achieve this a new design approach is needed that focuses on the long-term performance of building structures and its match with a technical composition.

Since a mismatch between the ‘use life cycle’ and ‘technical life cycle’ of building assemblies is dynamic and increasing, a strategic approach that manages this mismatch is proposed in this research. Furthermore, the objective of this research is to provide a design framework for high disassembly potential of building structures, which results in a high Transformation Capacity (TC).

The main assumption in this research is that a high TC of building structures relies on their high disassembly potential. TC is an indicator of building/system’s flexibility and environmental efficiency. High TC means high flexibility and low negative impact on the environment. In order to assess TC, a knowledge model is developed that takes into account various aspects of design for disassembly. The main difference between this research and earlier studies that deal with similar subjects is in the broadness of the aspects considered. Earlier studies deal predominantly with one aspect of transformation at the time, for example, spatial flexibility, social aspects and customisation of industry, or market aspects, etc.

This research treats transformation as a system, composed of interdependent sub-systems.

The three interdependent subsystems that form a transformational system are:

1. Spatial transformation (implies use requirements and functional decomposition);
2. Structural transformation (implies technical decomposition);
3. Material/element transformation (implies physical decomposition).

A transformable system has impact on the other major factors of sustainable development such as the social, environmental, and economic systems. This research focuses on the impact of the Transformational System on the Environmental System, although the other two are considered and discussed as well.

The framework of the theses

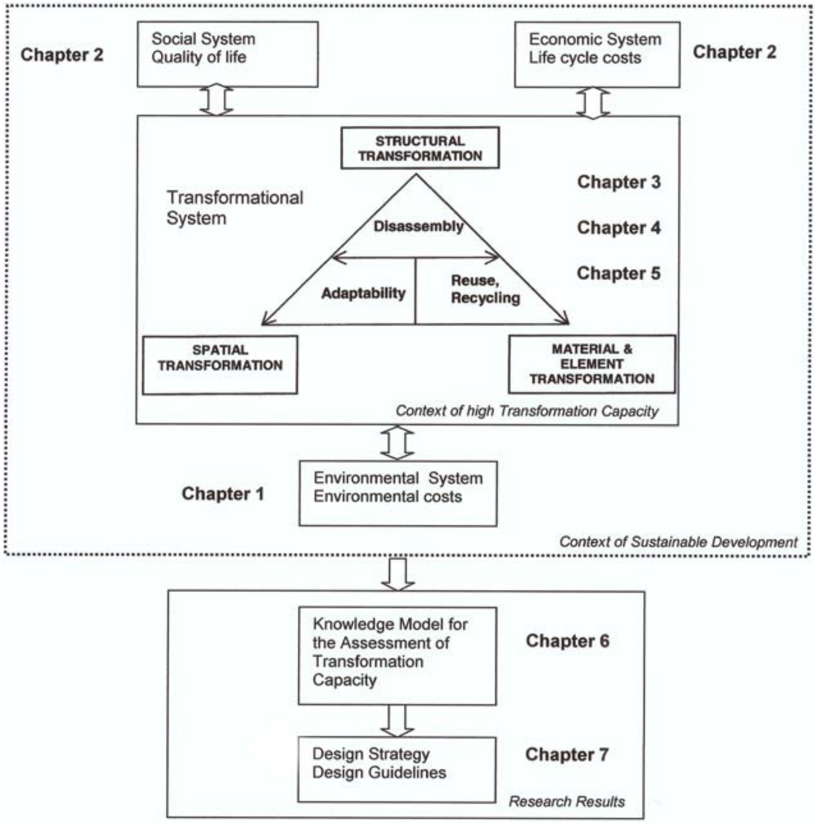
The framework of the theses is illustrated in Figure 1. The first two chapters discuss the context of sustainable development and the role of transformation in it. Chapters Three and Four address the context of design of highly transformable structures. Chapter Five focuses on the design aspects of disassembly. Chapter Six deals with a knowledge model developed to assess TC, in which TC indicates the flexibility of structures and their environmental efficiency. Chapter Seven suggests a strategy for the design of transformable structures based on a high disassembly potential. This is followed by the main conclusions and recommendations

Social relevance

Taking into account the negative impact that demolition and construction have on the environment, each new building should be built taking into account the TC of its assemblies. These secure the embodied resources in the building structure so that they can be used in the future as a source for new developments. Transformable structures are designed for reuse, reconfiguration, and recycling. Besides their environmental benefits, they offer building users the possibility to adapt them more easily to their needs and to save the investment costs for new materials. Considering this, one could say that the quality of a building in the future will be measured by the TC of its structures.

Overview of the theses

Figure 1 : a schematic overview of the theses.



Chapter 1
Sustainability and Technology

Cyclic processes must replace linear
ones to create sustainable development
(Agenda 21)

INTRODUCTION

“Time, is a three-fold present: the present as we experience it, the past as a present memory, and a future as a present expectation. By that criterion, the world of the year 2005 has already arrived, for in the decisions we make now, in the way we design our environment and thus sketch the lines of constraints, the future is committed.” [Dutt96]

By the year 2010 more then 50% of the world’s population will live in man-made environments and this percentages will increase rapidly. At the same time the emissions of carbon dioxide that cause global warming are expected to increase up to 45-90% and the total energy consumption will have by 2005 will have doubled (UN estimates). Recent studies have stated that the building industry is the greatest consumer of world’s natural resources and energy, as well as the greatest dumper of waste.
Accordingly, the main goal of the construction industry is to contribute towards global sustainability by using energy saving processes, reducing the use of natural resources and reducing waste production.
However, the conventional building industry has a limited understanding of building efficiency. Buildings are conceived as fixed and permanent structures although they may be subject to daily transformation. For that reason most building structures have to be broken down, in order to be changed, adapted, upgraded, or replaced. Their material flow is one-directional, starting from material extraction, and finishing with landfill. This results in huge waste production and material consumption. It is evident that such building practices rely on unlimited consumption of diminishing materials and energy resources, as well as the use of rapidly filling landfills.

Chapter 1 draws the relation between the state of the art in building construction and its negative environmental impact. It also discusses the search for new directions for bringing building construction closer to what is known as sustainable practice, whose aim is to divert linear material flows within industry into cyclic feedback loops. Examples are introduced that show evolution of natural systems from high consuming to adaptable structures, and the development of green product engineering.
Examples indicate that the crucial factor for successful transition from environmentally inefficient systems, which rely on resource stocks, to systems with efficient energy and resource feedback loops, is the design of complex adaptive structures. These, unlike simple highly consuming structures, are capable of achieving more with less.

In addition to that ‘Design for Disassembly’ (DfD) is seen as potential breakthrough in the conventional thinking about the nature and performance of building structures.

1.1 SUSTAINABLE DEVELOPMENT - THE MISSION

Since the 1960s, scientists have been warning that the earth has reached certain limits and that a more sustainable form of living ought to be found in order to preserve the living support system of the planet. This was documented by the fact that climate change has occurred due to the increase by 28% in the concentration of CO_2 in the atmosphere. Arctic sea ice area is now at 70% of the amount found in 1870, and is shrinking rapidly (EPA 2003). Forest cover is being lost at a rate of 10 million hectares per year (EPA 2003), and so on. These are examples that indicate direct threats to the planet, caused by industrial production and the modern way of life. However, it was only after the Norwegian Prime Minister published the book ‘Our Common Future’ in 1987, was sustainability recognised as an unavoidable joint mission of the whole world community.

The requirements put forward for the global community by the United Nations report by Brundtland in 1987 was seen by Gibson as “an attack on conventional thinking and practice”. Houwever, it recognised that at the same time it would be “suicidal to allow further undermining of ecological life support systems locally and globally.” (Gibson 2002).

Therefore, there has been worldwide agreement that the challenge faced by all is to achieve sustainable development that will protect ecological integrity over the long term, while improving quality of life. This is an extremely difficult task considering the economic prosperity of modern society is based on industrial systems that consume huge amounts of materials and energy on a flow-through basis, which results in pollution and the disappearance of bio-diversity. However while there is a growth in population, there is decline in the necessary resources to sustain this population.

1.1.1 The framework for Sustainability

As a part of MIT research that was focused on investigation of trends and factors that produce environmental stress, Speth developed the following equation:

$$\text{Environmental impact} = \text{size of population} \times \frac{\text{GDP}}{\text{person}} \times \frac{\text{environmental impact}}{\text{unit of per capita GDP}}$$

(Where GDP is countries gross domestic product, a measure of industrial and economic activity).

“The total environmental pressure is proportional to size of the population, its level of prosperity and the environmental effectiveness per unit of prosperity” J.G.Speth.

Speth defined the stresses on the environmental systems as being influenced by the need of the population that must be provided for, by the standard of living that population desires and the impact that technological processes have on the environment.

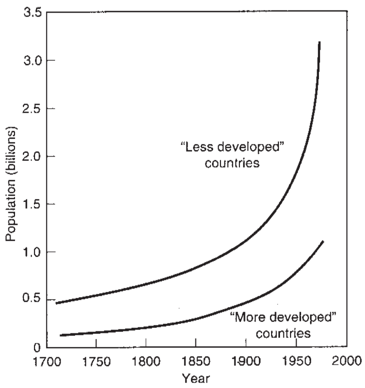


Figure 1.01: The population on earth over the past three centuries “More developed countries are the United States, Canada, Europe, The former USSR, Japan, Australia and New Zealand” T.E.Graedel & P.J.Crutzen –Atmospheric Change: An Earth System Perspective

Population sizes are increasing rapidly. There is an assumption that the world population of 5.6 billion people (1996) would rise to 8.3 billion people by the year 2025. (Figure 1.01)

However, the level of prosperity varies among different countries and regions. It can be expected that it will continue to grow - especially in developing countries.

The third term in Speth’s equation is an expression of the degree to which technology is available to permit development (economic and population growth) without serious environmental consequences and the degree to which available technology is deployed. This is primarily a technological term (Graedel).

Going back to the equation, one realises that the trends for the first two terms of the equation are strongly increasing. Populations and their prosperity tend to grow. Therefore, if environmental impact is to be reduced it is the third term in the equation (technological development) that offers the greatest hope for a transition to sustainable development. It is the modification of this term that is the central principle of sustainable design. In order to make a step towards more sustainable technological activity of industry, it is useful to understand the context of industrial development and its relation to the environment. The diagram in Figure 1.02 shows this relation.

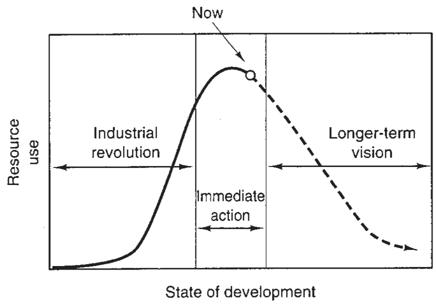


Figure 1.02: A schematic diagram of the typical life cycle of the relationship between the state of the technological development of society and its resulting environmental impact (Greadel and Allenby Design for Environment (1999))

The first part of the diagram shows a period of manufacturing of low recyclable products, during which the level of resource use and waste, increased very rapidly. This period followed the industrial revolution, which made uncontrolled use of available resources, and focused primarily on the consumption of resources. The second segment of the diagram illustrates the operation of industry today in which very small steps are made towards environmentally efficient production. The reason for this is that for the past three decades industries have largely been in the position of responding to legislation imposed as a consequence of real or perceived environmental crises. Such a mode of operation is reactive rather than proactive. To illustrate this one can take an example of the energy issue in housing. In order to reduce operational energy of the building (which has impact on CO_2 emissions), building became well insulated, what led to buildings with poor ventilation. This is especially true in housing. This solution has created new problems related to ‘sick building syndrome’. The main structure of buildings in many countries is primarily made of concrete. Concrete is made of earth-bound substances that contain Radon (a radioactive gas). Due to poor ventilation, the concentration of Radon in dwellings is often higher than what is allowed. According to the latest USA statistics, there are 800 new cases of lung cancer due to the radiation from radon in dwellings (Journal 30.01.2004).

Very often the result of ‘effect-solution’ approaches to problem solving are short-term solutions which do not get to the root cause of a problem and do not consider the full implication of actions taken. Such decision-making (as discussed above) can

be very damaging in the long run.
Number of current scientific reports demonstrate that the flows in the ensemble of industrial systems are so large that limits are setting in: the rapid changes in stratospheric ozone, increase in atmospheric carbon dioxide, degradation of water and soil resources, loss of habitat and bio-diversity and the filling of waste-disposal sites.(Adams 2003, VROM 2002, Doorsthorst 2000)
Many aspects of modern life contribute to the environmental stresses, but surely one of the most influential is a current pattern of use of natural resources by the technological activities of society, and the energy use and emissions of waste products that result.

The last part of the diagram is the long-term vision, which takes into account aspects of all life cycle phases of the resource consumption. Such an attitude would ultimately result with manufacturing of highly recyclable products and with life cycle impact on the environment being reduced to negligible proportions.

1.1.2 Sustainable building – global perspective

In order to understand the overwhelming impact that the construction industry has on shaping our common future, it is necessary to look at this sector from a global perspective. The construction industry is a vital sector of our society and is seen in many countries as an indicator of economic growth and prosperity. Building and construction contributes on average 10% of GNP, and more than half of the capital investment in all countries. The construction industry is estimated to have 111 million employees world-wide, and is therefore the world's largest industrial employer (CICA 2002). Nearly 50% of the earth's land has been transformed for human activities (strategy for sustainable development 2002), and more than 50% of the human population currently lives in cities, with this percentage increasing (CIB 1999).
Moreover, the impact of the building industry on the environment extends beyond the construction phase to include supply chain issues and the effects of post construction activities such as operation, maintenance and re-use of building (CRISP 1999). Therefore, the building construction sector is directly related to other major sectors such as mining, manufacturing, agriculture, and transport.
Including all the above-mentioned activities, this sector is accounted for 50% of global greenhouse gas emission (UNEP-IETC, 2002) that makes it the largest single contributor to greenhouse gas emissions globally (CIB 1999). In many countries

the construction industry accounts for up to 40% of materials entering the global economy (CIWMB 2000), 50% of waste production, and 40 % of energy consumption (Anink 1996).

Besides environmental and economic issues, there are also social issues such as quality of life, quality of housing, and liveability that are impacted by the building industry.
Taking into account its quantitative and qualitative aspects, the building industry can be seen as one of the most influential contributors to sustainable development.

Today as whole cities rapidly rise and fall, buildings are taken down and new ones go up, building sites and infrastructure are subject to continuous transformation.
Besides conventional buildings are not designed to meet the changing requirements of our society. As a result, buildings often have to be demolished in order to be adapted to new needs.

Nevertheless, no matter what the nature of the change is, everyday practice shows that transformation within buildings always involves demolition and waste disposal. This means that the impact of our current dynamic society and market economy on the environment is measured through the volumes of waste going into landfills and incineration, through the energy, dust and noise related related to the demolition activities, through the new materials and embodied energy that comes in place, as well as through additional investment costs.

Such highly inefficient building processes affect economic, environmental and social systems, and are a result of traditional building practices that focus on three competitive factors: construction costs, quality, and time. Generally, the main problem lays in the fact that developers, architects, and builders often visualise buildings as static and permanent and do not make provisions for their future transformations. Their focus is predominantly on optimisation of short-term values as construction cost, quality, and time. Contrary to this, the sustainable approach to building construction treats these traditional competitive factors as sub-factors that are part of a sustainable global system with main factors being environmental, economic, and social systems (Figure 1.03).

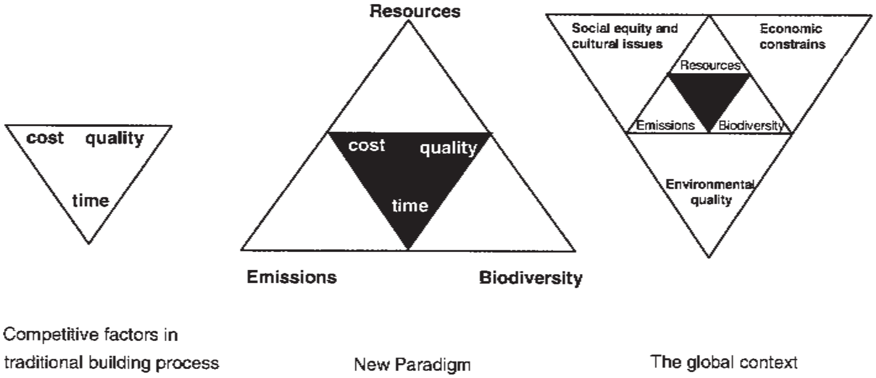


Figure 1.03: Progression to a Sustainable Approach to Building and Construction (CIB 1999)

In order to progress towards a sustainable approach in building and construction, the design focus has to go beyond the construction phase of building (which deals with optimisation of cost, quality and time) to incorporate long-term operational phases, as well as the demolition phase. These two phases account largely for the negative impact of the building industry on the environmental, and on economic and social systems.

In order to give a picture of technological activities within the building sector, the state of the art in building construction is now presented.
The following section discusses the negative impact that building construction has on environmental system.

1.2 TYPICAL END-OF-LIFE OF BUILDING STRUCTURES AND THEIR ENVIRONMENTAL IMPACT

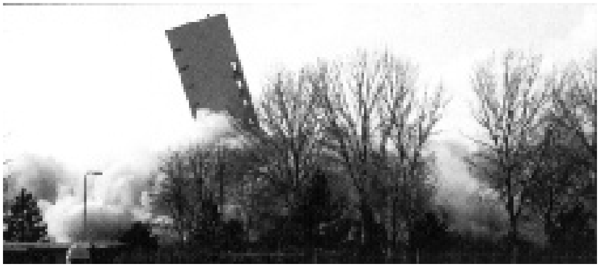


Figure 1.04: Demolition sequences with use of explosive

Most modern buildings today are made of prefabricated components designed to be mountable, but not demountable. For this reason assembly of buildings can be seen as a complex sequence of connecting carefully designed components and materials, a process that may involve thousands of people and fleets of machines (Crowther 1999). On the other hand, disassembly in the building industry usually involves a few bulldozers and some explosives (Figure 1.04 and 1.05). In this way, materials and energy brought into the construction of built structures are often thrown away at the end of the building's life cycle, together with tonnes of non-recycled materials, which go into landfills or incinerators. The reason for this is that buildings are not designed to be demountable. Their components are not designed to be reused and reconfigured, and materials that are often composed of composites are not designed to be recycled.

Buildings are not designed with the goal to recover their materials for a future use. The lack of potential for material recovery in the building industry can be best seen during the demolition phase of building, which is a typical end-of life of building structures.

The demolition process has two stages:
Stage one in the demolition of buildings is the stripping of building finishes in two steps:
1.Step one involves the stripping of reusable components. Those are mainly glass elements removed from the window frames, sanitary fixtures, wooden floor finishes, and radiators.
Phase two includes the stripping of plasterwork, service installations, pipes, and roof coverings. In the case of flat roofs, the roofing is removed and taken to a landfill. The roofing gravel, in case of a flat roof, is usually contaminated with PAH (polycyclic aromatic hydrocarbons) and should be treated as a chemical waste.
This phase of stripping a building produces a number of waste streams. The waste is transported to a sorting plant where they are separated in recyclable, burnable, and non-burnable materials. The burnable portions are incinerated in a waste incineration plant and the non-burnable portions are land filled.

Figure 1.05: Typical demolition sequences

2. After stripping of the building, the demolition of the rest of the building begins. When only the brickwork and concrete is left, the building is demolished floor by floor. Beams and wooden floors are removed with cranes and equaliser beams. The nails in joints are removed by punching. Brickwork is cut into sections and taken to a crusher plant. Most of the brickwork is not reusable because of the use of strong mortar that breaks only after the brick itself.

The concrete structure is cut up using breaker shears and taken to a crusher. In the past, concrete rubble was cut into smaller parts and iron was removed on site. Today, crushing plants have developed methods to handle large sections of concrete and to extract reinforcing steel using magnets (Figure1.06 and 1.07).

The demolition sequence of buildings with steel frames depends on the connections between structural elements.
If columns and beams can be reused, then the structure is disassembled. Otherwise the steel structure is cut up and sent to a steelwork.
Besides the use of cranes, equaliser beams, and breaker shears, demolition of buildings using explosives is also a common technique. It is often used for demolition of high-rise buildings. (Figure 1.04) This process involves high risks for the surrounding community and for demolition workers.

1.2.1 Material flow and waste in construction

As a result of demolition processes that reflect conventional methods of construction, the demolition of building structures produces enormous amounts of waste materials. In most countries this results in significant waste streams. In the U.S. demolition waste amounts to 92% of the total construction and demolition waste streams. (C.Kibert00)
According to the (EEA 03) the building industry in Europe produces 410 million tonnes of waste per year, with yearly increases of 9.7 million tonnes.
In the Netherlands, construction and demolition wastes amount to 18 million tonnes per year (VROM 2002).
Recent studies show that the largest quantities of wastes are minerals that originate from structures. They also show that due to contamination, a fairly large part of recycled material is of low quality. Furthermore, they are not designed to be recycled because they are often composed of hazardous materials or materials could not be

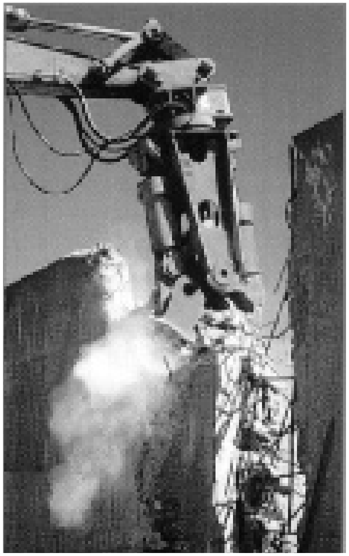


Figure 1.06: Crushing of the concrete on the demolition site before it is transported to the recycling plant.

Figure 1.07: Demolition sequences of the concrete structures using breaker shears

taken apart. This is often the case with masonry.

Ten years ago the total DCW (Demolition and Construction Watse) was 12.5 million. From this amount 3.6 million tonnes was waste generated during construction, and 8.6 million tonnes was demolition waste. (Table 1.1)

Table 1.1: Overview of the demolition and construction waste in the Netherlands in 1992

	housing	offices	roads and water buildings	total
construction waste	1.4	0.9	1.3	3.6
demolition waste	1.4	4.5	2.7	8.6
total DCW	2.8	5.4	4	12.2

Of the 12.2 million tonnes waste, the most common material was concrete/brick fraction that amounts to about 90% of total waste (Table 1.02) 85% of concrete is recycled and used as road base. This recycling is called 'down-cycling' since recycled aggregate cannot be reused and still reach the same quality of concrete. According to the Dutch building standard, 20% of recycled concrete can be used as a aggregate for new concrete. Aggregate made of recycled concrete cannot be used to make new concrete of high quality. Material that has this capability is for example aluminium or plastic.

Table 1.2: Overview of the demolition and construction waste in the Netherlands in 1992

	housing %	offices %	roads and water buildings
brick/concrete fractions	89	96	99
wood	8	0.9	0
steel	1.2	2.6	0
tarry	0.3	0.2	0
plastic	0.4	0.1	1
rest	1.2	0.5	0

product	million ton
concrete aggregate	0.8
brick aggregate	0.5
mixed aggregate	1.8
asphalt aggregate	0.7
hydraulically aggregate	1.0
sand	0.6
rest	0.5
aggregate from mobile demolitions	0.6
total	6.5

Table 1.3: Material use based on down cycling in 1992

Construction and demolition waste in the Netherlands amounts to 18 million tonnes in 2003. The total demolition waste in 2002 has increased more that 50% since 1990. This increase is greater than the economic growth in the Netherlands for the same period (Figure 1.09). On the other hand reuse of waste by recycling increased 20% (from 70% in 1990 to 90% in 2001). However, 90% of materials' recycling takes place within 'down-cycling'. This scenario is least beneficial for the environment, due to the degradation of materials and loss of embodied energy.

Composition of construction and demoli-

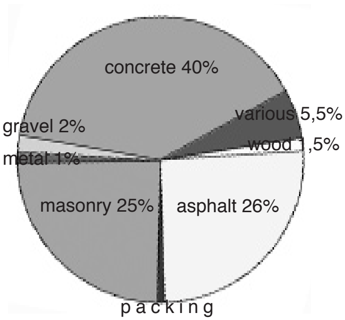


Figure 1.08

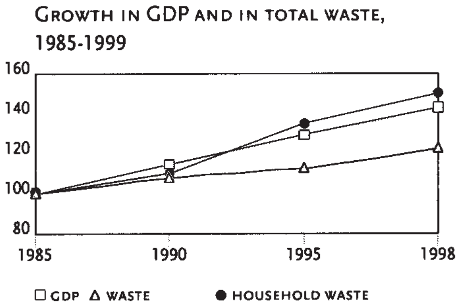


Figure 1.09

Figure 1.08: Building and demolition waste in the Netherlands 2001

Figure 1.09: Increase of the construction and demolition waste (C&DW) over the years

1.2.2 Embodied energy

Besides waste generation, another significant issue related to reuse of waste is embodied energy. Embodied energy is the energy required to produce or manufacture a product. This includes:

- Direct energy used in the manufacturing process,
- Indirect energy required to extract raw materials, transport them, and
- Energy needed to produce the infrastructure required for these production activities.

Currently, there are no reliable embodied energy analyses due to the lack of reliable process analyses. However, different studies show that embodied energy can range from 30-50% of total life cycle energy.

Research done by Ray Cole at the University of British Columbia's School of Architecture compares embodied energy with operating energy. Cole compares two types of houses: energy efficient and traditional. His figures reveal an embodied energy for both versions of the house that is equal to several years' worth of heating energy, which is the major component of home operating energy in Canada (see Table 1.4). According to Cole's data, it follows that the more operating-energy efficient a house is, the larger percentage embodied energy will be of the structure's total energy.

Home type, location	Heating Energy MM Btu/year (Gj/year)	Embodied Energy MM Btu (Gj)	Embodied Energy in years of Heating energy
Conventional, Vancouver	101 (107)	948 (1,000)	9.4
Energy-efficient, Vancouver	57 (60)	1019 (1,075)	17.9
Conventional, Toronto	136 (143)	948 (1,000)	7
Energy-efficient, Toronto	78 (82)	1019 (1,075)	13.1

Table 1.4: Embodied Energy versus Operating Energy

Another study, done by Andrew Buchanan and Brian Honey of the University of Canterbury in New Zealand concluded that the energy required to manufacture a house is of a similar order of magnitude to the energy required to heat the house over a 25-year life span.

The embodied energy in recycled building materials is generally less than that contained in new materials. Recycling provides easily obtainable manufacturing feedstock. There is very low extraction energy associated with recycled materials. Although manufacturing with recycled feedstocks can involve transporting, cleaning, and sorting the recycled materials, this often requires far less energy than manufacturing from a virgin resource, which must be extracted and refined before use (Mumma 1995).

Table below gives an overview of energy required to produce materials form virgin material and energy saved by using recycled material. (Table 1.5)

	Energy required to produce from virgin material (million Btu/ton)	Energy saved by using recycled materials (percentage)
Aluminum	250	95
Plastics	98	88
Newsprint	29.8	34
Corrugated Cardboard	26.5	24
Glass	15.6	5

Table 1.5
Source: Reducing the embodied energy of buildings, T. Mumma, Home Energy Magazine, Jan/Feb 1995).

However, this advantage of recycling (especially of down-cycling) cannot be taken for granted in all situations.

Embodied energy in concrete

Concrete has a high recycling rate in the Netherlans of up to 90%. (Doorsthorst 2000, Kowalczyk 2000) It is mainly used as a road base. However, a few international case studies have shown that using down-cycled crushed concrete as aggregate for road base used 37% more energy than using new aggregate (MacSporran, et al 94). Although this study was limited to energy consumption issues only, it does show that recycling is not necessarily the environmentally beneficial option, and that a holistic life cycle assessment needs to be made. Moreover, if down-cycling of material takes place, degradation of material occur. Aggregate that is made of crashed concrete can not be used to make new concrete of the same quality. (Figure 1.10) According to the Dutch norms, only 20% of recycled aggregate can be used for the new concrete elements.

Figure 1.10: Concrete recycling plant in Germany. Photos represent the recycling process from selection of concrete fractions, extraction of the iron by magnets, to the production of the final recycled aggregate, which is used for the road base

Steel is, on the other hand, a material that has huge embodied energy. Thanks to its recycling capabilities, it can regain the original quality of material and some of its embodied energy.

Embodied energy in steel products

ECSC (European Coal and Steel Commission) examined the environmental burdens of all processes associated with the life cycle of selected steel construction products in the Netherlands, Sweden and the United Kingdom. These processes have been systematised into five phases (Figure 1.11):

Phase 1 Production of 'intermediate' (semi-finished) steel products, e.g. coil, plate, sections, etc.

Phase 2 Production of finished steel construction products. Transport from the steel mill or stockholder to the manufacturing facility is included within this phase.

Phase 3 Construction phase (to include on and off-site erection, fixing and assembly of selected products for specific applications. Transport to the construction site is included in this phase).

Phase 4 In-use phase (to include product life span, functional maintenance, repair and replacement of products within a structure or building under different environmental exposure and aesthetic conditions).

Phase 5 End-of-life phase (to include demolition and deconstruction activities, re-use and recycling rates, scrap processing activities and final disposal). Transport from the deconstruction site to either the scrap handling and/or waste treatment site are included in this phase.

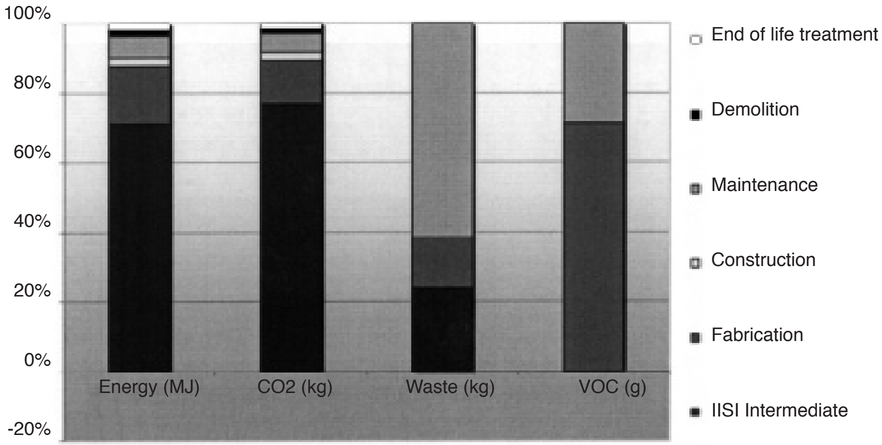


Figure 1.11: Major contributions to the environmental pressure within the total life cycle of structural steel, excluding allocation

The environmental impact per life cycle phase has been presented through four categories: primary energy consumption, CO_2 emission, non-combustible waste generation, and VOC emissions (Figure 1.11).

For all products studied, the overall contribution of the steel production phase is dominant. Considering energy consumption, steel production typically accounts for 75% of the whole life cycle impact (ranging from 55 to 89%). This dominance is reflected in the CO_2 emissions data and results principally from the means by which energy is generated in Western Europe, i.e. predominantly from fossil fuels.

Analysis of end-of-life scenarios of steel products illustrates that at the end-of-life 83% of steel products are recycled, 14% of steel products are reused, and 3% land-filled.

Figure 1.12: Steel recycling plant

Reuse would save energy consumption needed for the production of semi-finished products. This typically accounts for 75% of the whole life impact of steel products. (ECSC). Increasing the percentage of reuse can decrease the environmental impact of steel.
After reuse, recycled steel is also an interesting option (Figure 1.12). Steel rarely comes to the down-cycling level because it can be fully recycled and used for new structures. Moreover, production of recycled steel uses 50% less energy than primary steel production. Currently 40% of world steel production comes from recycling plants. The goal of the steel industry is to increase this percentage in coming years close to 100%, by using existing structures as a resource pool for steel production.

Embodied energy in Aluminium products
Primary aluminium production is energy intensive and because of this has been criticised on the assumption that the volume of embodied energy in some way equates with the volume of greenhouse gas emissions, as a result of electrical generation and smelting processes. However, this is usually not the case. The embodied energy approach takes no account of differences between energy sources. According to a

recent IAI study, 60% of the electricity supplied to the world's aluminium industry's smelters is produced using non-fossil fuels, which do not result in greenhouse gas emissions (Figure 1.13). (International Aluminium Institute 2000)

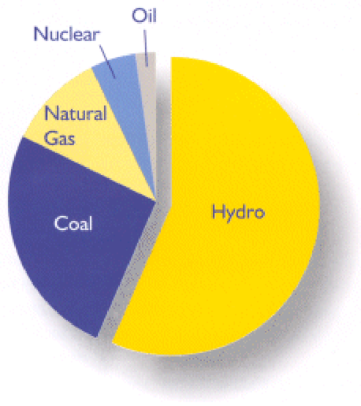


Figure 1.13: Energy sources for aluminium production

As almost all aluminium used in construction is recycled, the considerable energy invested in the production of primary aluminium can be reinvested into other aluminium products.
Aluminium component have a very long life cycle (between 30 and 50 years). Aluminium stored in such long life products is therefore in effect stored for future use. At the end of its useful life a product's aluminium content can be used again and again without loss of quality, saving energy and raw materials.

Reuse
Generally it is assumed that recovery of materials for reuse is more beneficial from an energy and resource point of view, than for recycling. Reusing materials can reduce the energy needed for the production of new materials. Accordingly, reduction of environmental damage, in particular greenhouse gas production, can be achieved.

Dutch waste policy
The main pillar of the Dutch waste management policy is prevention, which involves preventing or reducing the waste actually generated. (Table 1.6)

Ladder of Lensink 1980	**Delft Ladder 2000**	**relevant processes**
1/ Prevention	1/ Prevention	long term planning
2/ Element reuse	2/ Construction reuse	disassembly
3/ Material reuse	3/ Element reuse	disassembly
4/ Useful application	4/ Material reuse up cycling	disassembly
5/ Incineration with energy recovery	5/ Material reuse down cycling	disassembly
6/ Incineration	6/ Useful application	chemical processing
7/ Landfill	7/ Immobilisation with useful applicatio	chemical processing
	8/ Immobilisation	chemical processing
	9/ Incineration with energy recovery	burning
	10/ incineration	burning
	11/ Landfill	disposal

Table 1.6: Hierarchy of the most preferred options for sustainable construction

After prevention, reuse is another preferable option. Product and material recycling

are the fourth and fifth rungs of Ladders (VROM -waste policy 2002). Waste prevention translates into a need to
design materials, goods and services in such a way that their manufacture, use, reuse, recycling, and end-of-life disposal results in the least possible generation of waste.
Particularly in growing economies, waste prevention is a heavy challenge in order to achieve decoupling of waste generation from economic growth.

In its fact sheet The Dutch Ministry of Housing, Spatial Planning and Environment specifies Dutch waste policy through the following points:

- Devising and adopting instruments to encourage or enforce prevention, recycling and reduce waste going into landfills
- Setting environmental and policy constraints for waste management
- Creating the framework for waste management planning at the national level
- Spelling out the responsibilities of producers for disposal of their products in the waste phase
- Regulating imports and exports of waste.

Nevertheless, Dutch government concluded in 2002 that the amount of waste is growing faster than anticipated, and that recycling is not keeping pace.

1.3INDUSTRIAL ECOLOGY AND NATURAL SYSTEMS

Some have suggested that industrial systems could use the metaphor and behaviour of biological systems as guidance for sustainable design. This concept reminds one in many ways of the interaction between industrial and natural systems. The existence of the first primitive biological systems had essentially no impact on available resources since the usable resources were so large and the amount of life so small. The use of resources at that early earth's history by primitive biological systems can be described as linear. That is, the flow of material from one stage to another is independent from other flows. As early life forms multiplied, external constraints on the unlimited sources changed and the skins of the first systems began to develop. These conditions led to the development of feedback and cyclic loops as an alternative to linear materials flows. Kibert elaborated this further in his article ‘Construction ecology and metabolism’ stating that current industrial systems are the equivalent of ecosystem R-strategists* (pioneer species) that rapidly colonise areas laid bare by fire or other natural catastrophes (Kibert 2000). Their strategy of maximum mobility and reproduction invests all their energy in rapid growth and minimises investments in structure. R-strategists are mobile, surviving by being the first at the scene of a disturbance and securing resources before they erode away (Begon 90, Holling 95).

However, when the resource base has been expended, their populations diminish to very low levels. They are not competitive in the long run and only do extremely well at competing with each other in a loose ‘scramble competition’, eventually losing out to better strategies. In natural succession, K-strategist* species supplant R-strategist species because they spend less energy on generating seeds and more on systems such as roots that enable their survival during periods of lower available resources. K-strategists live in synergy with surrounding species and are far more complex than R-strategists.

K-strategists unlike R-strategists, are not mobile, but survive longer at higher density, by developing highly efficient resource and energy feedback loops. K-strategists invest more in structure than mobility, which is the template around which their complex interrelationships efficiently conserve the flow of energy and resources.

It could be said that industrial systems have a same pattern of survival. Industrial activities of today can be compared with the R-strategist. The structures are primitive and inflexible recognising only linear material flow, with little or no material recovery from waste streams.

Closed-loop K-strategist industries with full materials recovery do not exist at the moment, due to poor product design and lack of technologies. The main difference between the two strategists is in the efficiency of their structures. Simple primitive structures rely on the stock of resources, while complex structures are adaptable to different conditions and more efficient in resource consumption; therefore they can last longer.

* (The R-strategy is characterized by a high rate of propagation. It occurs especially with species specialized on colonizing new habitats with variable conditions or with species with strongly fluctuating population sizes. The K-strategy, in contrast, describes a regulated, density-dependent propagation in view of the capacity limit of the habitat K. It occurs in species living in stable habitats, where a high rate of propagation is of no advantage. It is regarded as more progressive than the r-strategy in an evolutionary sense. In nature, all conceivable transitions between these two extremes occur. A given species will therefore mainly adopt one strategy, even though shares of the other strategy cannot be overlooked. Sometimes, extern circumstances like unpredicted changes of the living conditions trigger a change from one strategy to the other.)

1.4 FROM LINEAR TO CYCLIC LIFE CYCLE MODEL

Material flows in the building industry has a dominant linear direction in which material systems are running down. (Crowther 99) Such material flow is often defined as a once-through linear system passing from raw materials extraction, through materials processing, assembly, use, and finally to demolition. Such systems recognise one end-of-life scenario, waste disposal, which is the result of demolition (Figure 1.14).

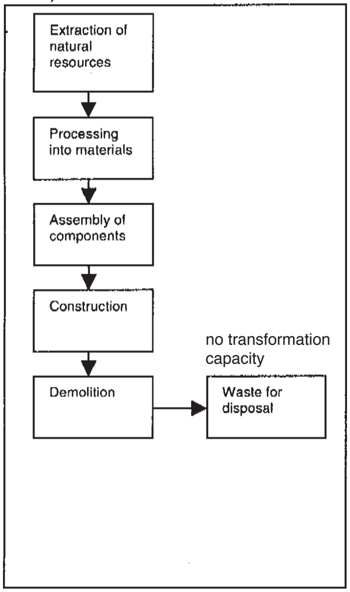


Figure 1.14

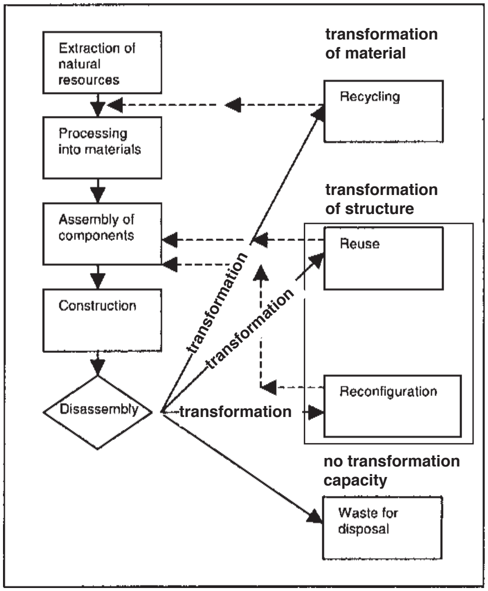


Figure 1.15

Figure 1.14: Dominant linear model of life cycle of materials and components

Figure 1.15: Life cycle of materials and components for improved sustainability

If we look at biological ecosystems, that become ultimately sustainable, it is recognised that they have evolved over a long period into completely cyclic systems. In these systems resource and waste is undefined (Graedel), since waste to one component of the system represents resources to another. (Figure 1.15)

The ideal use of materials and resources available for processes in building industry would be one that is similar to the above-mentioned cyclic bio-system.

In order to change conventional linear material flow within the building industry, it is necessary to provide more environmental end-of-life cycle scenarios for building materials in place of landfill and incineration. A number of examples from other industries indicate that if the act of demolition is replaced with disassembly, conventional material flow can be diverted towards reuse, reconfiguration, and recycling of materials and components. This suggests a more cyclic life cycle model, one that provides transformation of materials during different stages of product life cycles. Such a model offers a number of end-of-life cycle options for a building's materials and components (Figure 1.15).

1.5 DESIGN FOR ENVIRONMENT IN PRODUCT INDUSTRIES

At the moment that each node of product life cycle (Figure 1.15) performs operations in a cyclic manner or organises to encourage cyclic flows of materials within the industrial system, they evolve into more efficient systems regarding material flows.
This mode of operation has been recognised within industrial and product design practises as 'Design for Environment' strategy. Many automobile and computer industries have an established program of product retrieval for disassembly (Rosenberg 1992). These industries recognise different end-of-life cycle scenarios of the product such as: reuse, maintenance, remanufacturing, recycling (Figure 1.16 and 1.17).
Buildings and products as cares cannot be compared when it comes to the scale, complexity of requirements and structures. These differences result in different development and marketing strategies. Houwever, what they do have in common is the fact that their technical composition follows the similar principles. In other words configurations of their parts are result of careful consideration and integration of functionality, technology and physical integration. In other words, configuration of bought building structures just as structures of cares, airplanes or photo camera are result of integration of number of parts that have different functionalities. The allocation of functions into materials and arrangement of materials into components represent the performance of building components as well as care or computer component with respect to disassembly. In that respect the way car and other product industries have integrated issues of environmental design and replacement of individual parts can be recognised in the building context that aims at design of buildings whose components can be replaced and reused elsewere.
Their principle of Design for Environment involves the following design strategies:
Design for Reuse:
This scenario is based on prolonging the life of a building or component by dismantling components at the end of their functional life cycle, and reusing them in new combinations. This is seen as the best environmental option because it uses minimum

type of material	%
metal	74
rubber	5
plastic	11
glass	3
other	7

% of materials used in car assembly

Table 1.7: End of life vehicles in the Netherlands (collection point) and percentage of materials used in car assembly. 86% of the material is recycled in the Netherlands

energy and material to close the loop of a component's life cycle.

For reuse of car-parts, manufacturers and importers established the so-called Auto Recycling Netherlands (ARN) in 1993. This has led to increased material recycling and has had a beneficial effect on the operations of vehicle dismantlers (Table 1.7). Participating companies are already taking in 90% of end-of-life vehicles, and some 86% of the materials are being recycled (Figure 1.18). (VROM July 2001)

Design for Remanufacture:

This strategy involves reconfiguration of existing component or system to restore its condition to "as good as new". This can involve reuse of existing components, and replacement of some component parts, and quality control to ensure that remanufactured products meet new product tolerances and capabilities (C.Madu01).

Figure 1.16 left : Replaceable body parts of a car
Figure 1.17 right: Replaceable interior parts of a car

Figure 1.18: Reuse of car components. 'End-of-life vehicles' program

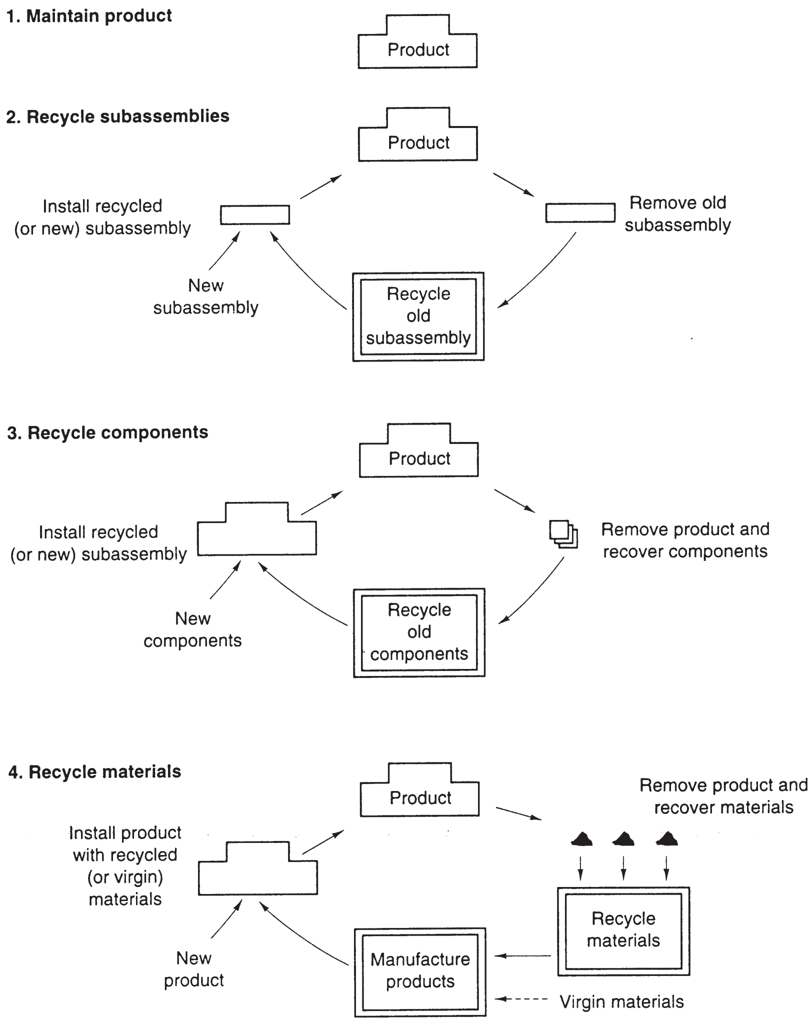


Figure 1.19: The hierarchy of the end of life options in product industries for the closed cycle material flow

Good examples of successful remanufacture strategy are Kodak's single use camera, products by Xerox, computer by Siemens, etc.

Design for Recycling

This recognises the fact that many of the earth's landfills are filling up at an alarming rate. Furthermore, many of the 'deposits' are hazardous and unsafe. Therefore, it is important to design 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 safely (down-cycling).

Design for maintenance

DfD should insure quick and efficient separation of components. Recently BMW designed its Z-1 sport car with an all-plastic skin designed to be completely disassembled from its metal chassis in 20 minutes. The car has proven to be much easier to repair, because damaged components can be readily removed and replaced.

Here discussed end-of -life options are illustrated in the figure 1.19.

Application of Design for Environment strategy at Siemens Nixdorf for example means that in 90% of Siemens 'eco-computers' is able to be reused.

Siemens Nixdorf has adopted the following three steps towards greater sustainability:

- Customers can hand-over their used computers to Siemens. Siemens tries to find a customer for the computer after upgrading it. These computers can be sold for about 10 to 33% of their initial price.
- Reuse of parts and components:

Computers that cannot be sold are disassembled in the Siemens recycling center in Paderborn (Germany). Valuable components such as power supply units, entire printed wiring boards and valuable electronic components are reclaimed for reuse. These parts are tested according to the quality requirements for new products. Correct parts are being used as spare parts for upgrading and repair of other computers.

- Recycling materials for new devices:

The computers and components that are not reused are brought to material recycling. The materials go partly back to the Siemens manufacturing plants for computers.

Kodak Single-Use Camera has developed one of the most successful environmental and business strategies.

Recycling of Kodak Single-Use Camera (SUC) is a three-point process that involves the active participation of photofinishers and a strategic partnership with other SUC producers. Photofinishers return the camera after processing the Kodak film.

Kodak details this process on its Website details :

Step 1: Photofinishers ship the SUC's to three collection facilities around the world. Through the strategic partnership with other SUC manufactures they jointly accept

each other's products. The products are sorted according to the manufacture and camera model.
Step 2: Kodak cameras are shipped to a subcontractor facility for processing. The packaging is removed and batteries in the camera are recovered. The camera is cleaned up and undergoes visual inspection. Those parts that could be reused are retained after rigorous quality control. Generally, old viewfinders and lenses are replaced. New batteries are inserted.
Step 3: The SUC is then shipped to one of Kodak's three SUC manufacturing plants. Here final assembly takes place. New packaging made from recycled material is added and the camera is ready again for use.
Each year over 8 million electrical and electronic equipment is discarded in the Netherlands (Figure 1.20). This includes some

- 90 k-tonnes of refrigerators, dishwashers, etc,
- 24 k-tonnes of TV's computers etc
- 20 k-tonnes of vacuum cleaners, coffee makers etc

Introduction of refundable deposits encourages product recycling.

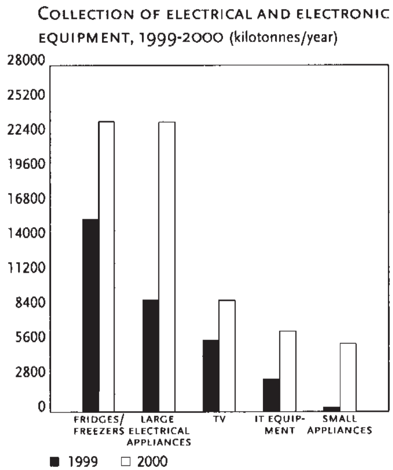


Figure 1.20: Collection of electronic and electrical equipment. (VROM 2001)

Furthermore, producers can be required to take back and reprocess their products. Producer responsibility has already been introduced for various products either on a voluntary or regulatory basis.

1.6 TECHNICAL PROCESSES THE KEY FOR SUSTAINABILITY

In an ideal case one can adopt as a goal that every Kjoule of energy used in manufacture should produce a desired material transformation; 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 design life.
Implementation of such an approach is intended to accomplish the evolution of manufacturing from linear to semi-cyclic, and finally to cyclic processes, by understanding the interplay of process and material flows and by optimising the set of considerations involved. (Figure 1.21)

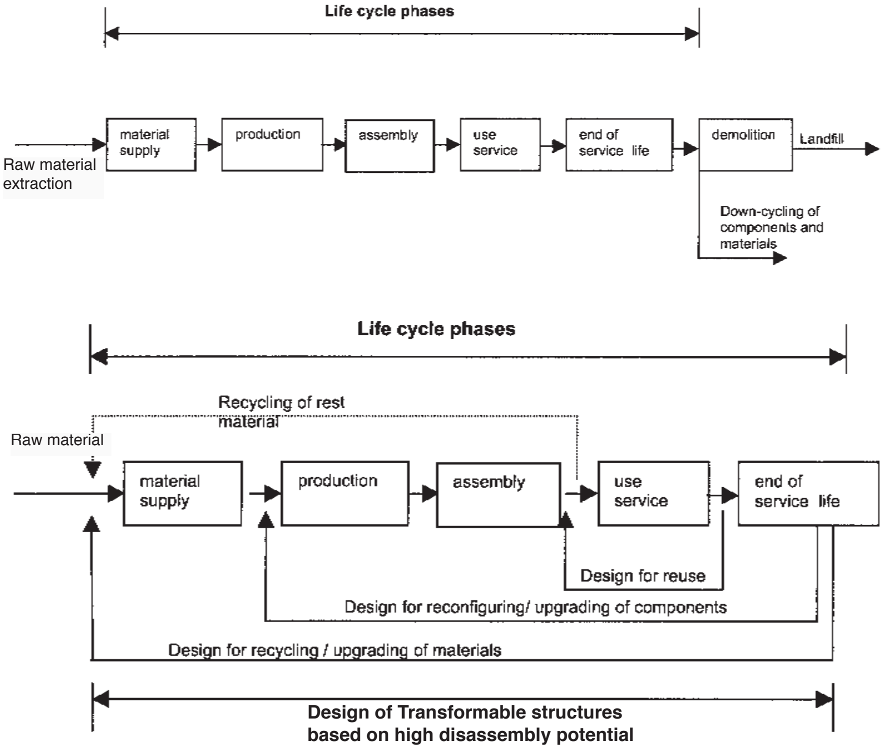


Figure 1.21: From linear to cyclic material flows in the building industry by introduction of processes that stimulate transformation on all material levels

Processes are the techniques by which products are made, for example, production of glass from lime, soda ash, and sand. Processes are the ways in which feedstock materials of one sort or another are transformed into intermediate materials. Thus, processes define much of the flows of solids, liquids, gases and energy into a manufacturing facility and are responsible for much of the flows of solids, liquids, gases leaving that facility (Greadel and Allenby).
In the building industry processes are the way in which elements are transformed into components, components into systems and building. Thus, they define the flow of materials and energy during construction and are responsible for flows of materials and energy from building sites.
The way in which building parts are put together has a great effect on whether or not a part of the building or the whole building is recycled after its design life. This is independent of whether its materials were wisely selected or not. In other words, the building process is responsible for the extension of the life cycle of the building and its components, and ultimately for the reduction of waste and use of raw materials.

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 are designed for such end-of-life scenario. This means that 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 consumption and increased waste production, but also in the lack of spatial adaptability and technical serviceability of the building.

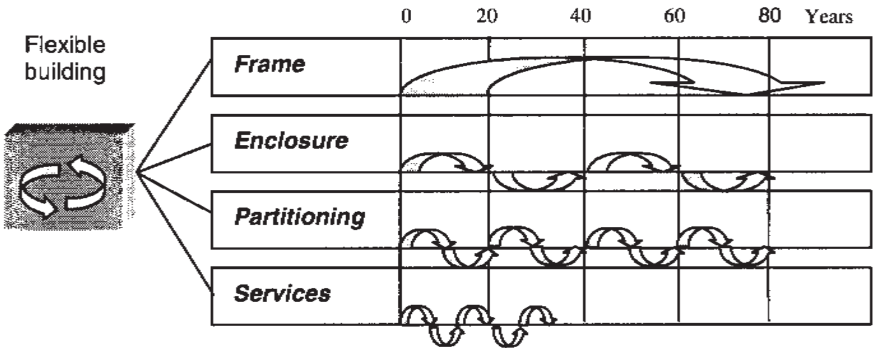


Figure 1.22: Diferent degrees of durability of building parts.

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 1.22)
Nevertheless, it is quite normal for parts with short durability to be fixed in permanently, preventing easy disassembly.
Therefore, at the end of components or building service life there is usually little option but for demolition, with associated waste disposal.
If we recognise the potential of disassembly, it is possible to divert the flow of materials from disposal and save the energy embodied in them by avoiding the demolition process.

Taking this into account the design of sustainable building runs the danger of being carried out on an ad hoc basis without disintegration aspects of the building structure being an integral part of the design process (Figure 1.23). 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, to remanufacture or recyclethem (Figure 1.24 and 1.25).

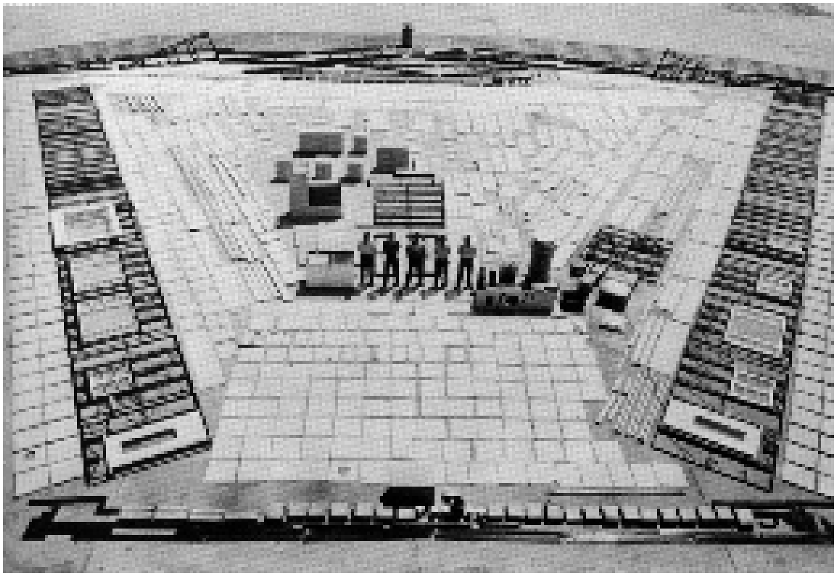


Figure 1.23: Building components of the Lustron-house (tussen traditie en experiment: De wondere wereld van de woning Jan Westra 1990)

This 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 such open building systems and components in order to be able to reconfigure or to replace them later on.
Ultimately the sustainability of design in the future will relay strongly on disassembly potential of building assemblies.

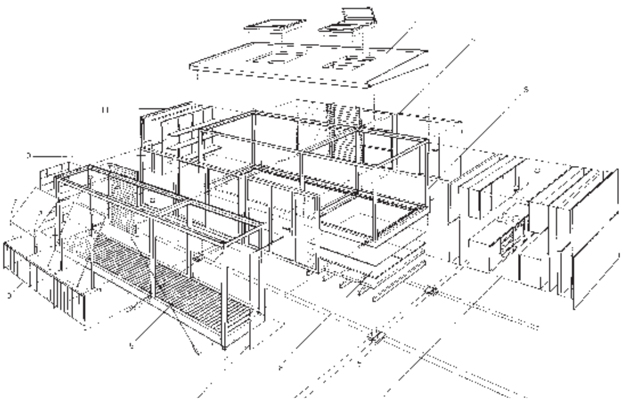


Figure 1.24: Demolition of one part of the shopping center in Rijswijk, The Netherlands 2000

Figure 1.25: Design of European House for Disassembly by Richard Hordon (Detail 00)

In order to increase a building's potential to be disassembled, we need to change our perception of the building technical composition from being permanent and fixed to being changeable and open. Such dynamic structures allow for modifications according to new requirements and recovery of materials and components for reuse, reconfiguration, and recycling. Finally, such structures allow existing and new building stock to serve as primary material sources for new construction, rather than harvesting resources from the natural environment.
Design of transformable structures based on high disassembly potential can be recognised as the key to sustainable construction.

The main discussion in this thesis relates to principles of DfD in order to propose guidelines for design of structures with high transformation capacity, which is an indicator of environmentally responsible architecture. In addition, economic and social aspects of such a design approach are discussed.

1.7 SUSTAINABLE CONSTRUCTION AND POLICY MAKING

Besides environmental factors there are also significant economic factors, which favour material reuse rather than material extraction.

Analysis of the end-of-life cost of consumer products indicate that the DfD scenarios can be appreciated by plotting the costs of different disposal options against the number of steps required for product disassembly (Graedel). If the product is to be landfilled, the highest costs generally occur if no disassembly at all is performed. This is because the volume and difficulty to handle the product is at its maximum. The costs decrease as some disassembly is performed, but before many steps have occurred. The end-of-life costs of the product can be minimised if the product is designed to be disassembled in few steps. If many disassembly steps are required, than the landfill becomes a preferable option (Diagram 1.1).
Therefore, DfD becomes economically a more interesting option when governments set rigorous standards for landfill sites and incinerators. A landfill tax tends to make these forms of disposal expensive, thereby encouraging recycling. The average charge for the landfill of non-hazardous waste has risen from a few euro/tonne in 1975 to about 110 euro/tonne in 2000 excluding VAT tax. Furthermore, landfill of many types of waste is prohibited (VROM 2002).

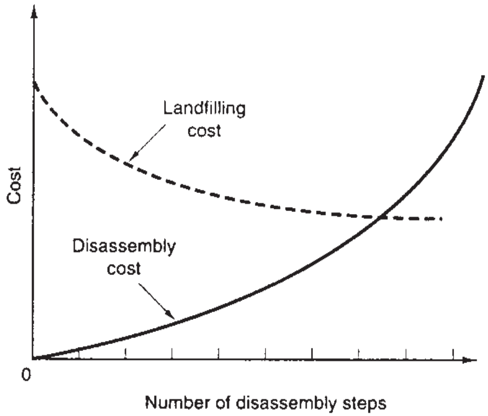


Diagram 1.1: Conceptual relation between the number of disassembly stapes of the products and landfill costs

A tax on the landfill of waste has become a widely used instrument and is now in use in nine Western European countries. The tax has been applied for several reasons, including the stimulation of waste reduction, reuse and recycling, to raise revenue, and to internalise landfill costs. More than EUR 1.7 billion is raised each year in western Europe (Kirk McClure Morton, 2001). While the influence of landfill taxes on reducing the generation of some waste streams (e.g. municipal waste) is questionable, landfill taxes do provide price signals, which should stimulate the adoption of more sustainable waste management practices.

It is interesting to note that besides the landfill tax there are other economic factors that can play a role in promoting material recovery.
In 2002 the Dutch Ministry of Transport, Public Works, and Water Management made an analysis of sand excavation from rivers.
Sand is an very important building material and its use greatly increases every year, since it is used as a base for mortar and concrete (materials frequently used in building construction).
In order to keep up with the yearly sand production, rivers should grow much deeper in the Netherlands. However, such initiatives are in some areas on the cutting edge of technical and economic feasibility.
In order to achieve this, huge investments are needed that would raise the costs of sand, and building construction in general. For this reason, the government is looking into a possibility to stimulate development of alternative materials, recycling techniques and building methods that would help reduce sand excavation.

Taking into account the dominant role that the building industry has in the world’s societies and the role it can play in providing a sustainable development, serious efforts should be made by all parties involved in building construction in finding alternative ways of building.
Introduction of an eco tax for each new development would give some motivation to all parties to search for these alternatives.

Chapter 2
Building Transforms

All buildings are predictions.
All predictions are wrong
(Stewart Brand 94)

INTRODUCTION

Building Transforms
Acceleration of change imposes different construction, operation and developing patterns on the built environment.

Chapter 2 reflects on ever-changing market activities driven by shifts in economies, diversity in working and living patterns, and the constant migration of populations. Recent trends in the housing and office markets indicate that the rate of change is accelerating, and that the cycles in building use are becoming much shorter. Consequently, dynamic activities developed in response to these changes need an environment that will provide the necessary flexibility. However, existing building structures are not designed for change. This is why more than 60% of yearly building production in the Netherlands iinvolves the partial and total demolition of existing structures and construction of new ones.
One can argue that existing structures are in large part responsible for the degradation of the environment, due to the tonnes of waste materials that become burdens to society. Taking into account the dynamics of construction activities, this burden constantly increases. If building practice does not evolve towards flexible building methods that stimulate reuse and recycling of building products, the disproportion between environmental degradation and sustainable development becomes unbridgeable.

Besides the negative environmental impact that conventional building methods placed in the context of changing society create, these methods are also economically unfeasible, since their life cycle costs are rising dramatically. A fast-changing society in transition towards more sustainable development needs technology to change.
This chapter argues that improvement of a building's capacity to adapt to new requirements extends its service life, and is the only way to bring bought costs and consumption of natural resources in balance with sustainable development.

The key issue in sustainable construction is recognised as the development of design strategies that transform inflexible building structures into dynamic and flexible ones, whose parts can be easily disassembled and later reused or recycled.

2.1 DESIGN FOR PEOPLE'S NEEDS

In Chapter 1, the position of this research in relation to one aspect of sustainable building is discussed.

Besides conscious use of building materials, another aspect of sustainability is improvement in the quality of life. Although these two aspects are different, they cannot be separated. As already shown in Speth's equation, environmental stress grows with the increase of people prosperity. The greater the prosperity, the greater is industrial production. However, if products are designed to adapt to people's needs, they last longer; otherwise, they are thrown away. This is exactly the point where environmental stress begins. Therefore, another component of sustainable construction is consideration of the diversity of people's needs, which can have environmental and economic benefits.

Richard Horden quoted in an interview with the German magazine Detail "A person who designs a camera will make it as small and light as possible, so that it is easy to carry, looks good and is appropriate to the person who uses it. The same principles should also apply to modern building." Buildings should be seen as products created to answer people's needs and not to treat these needs as uniform. Buildings should be able to adapt to different life phases of their users and to maintain building standards. Human behaviour does not remain constant. Even if we repeat the same activities every day we may approach them in different ways, as circumstances and moods dictate. (Figure 2.2)

In order to be responsive to users' needs, buildings should be able to accommodate changes from morning to evening, from place to place, from lifetime to lifetime (Figure 2.0 and 2.1).

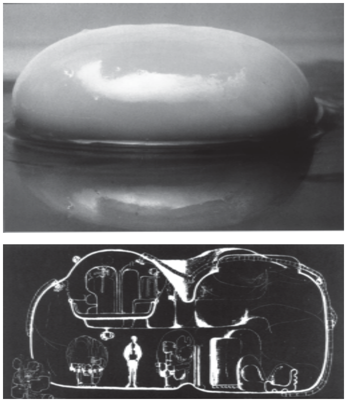


Figure 2.0: Adaptable spaces above: Source, Future Systems ' For inspiration only' (Future systems 1996) bellow: Source, Archigram Living Pod (Greene 1995)

Figure 2.1: Changes from morning to evening, from place to place from lifetime to lifetime. Caravan designed by Bohtlingk.

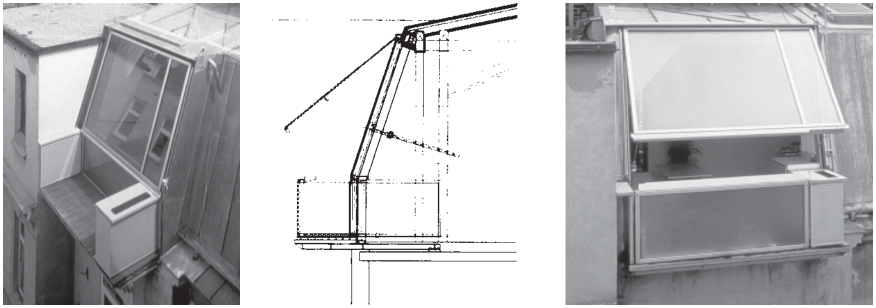


Figure 2.2: Tranformation with seasons, Appartment in Vienna, designed by Eichinger oder Knechti (Cuito2001)

Each new stage in life of users (from growing up to getting old) brings new sets of requirements to the surrounding environment.
If these requirements cannot be met within the context of inhabited spaces, these spaces are abandoned. This, for example, is the problem with social housing in the Netherlands. Decision-making on construction of dwellings was based on the short-term view of the current state of housing, and not on a long-term survey of users' needs and market conditions.
Therefore, most apartment blocks are demolished because of their inability to adapt to new requirements. It has been recently reported that demolition contractors in the Netherlands expect to demolish hundreds of thousands of apartment blocks in the coming decade. This will result in the creation of 25 million tonnes of waste materials each year.

Recent changes in technologies and society, coupled with changes in the lives of users, dynamic market activities, and environmental awareness, justify the need for new planning approaches that focus on buildings as economic and sustainable solutions during their whole life cycle. Conventional building cannot facilitate such demands.
Apartments were built to minimum standards to satisfy basic needs. The development of housing projects today has a similar strategy. Although energy and acoustic performance has improved, spatial performance has remained at a very low level, since the spatial system is unable to transform from one use pattern to another.

The main problem facing building transformation today is the fact that in the past, developers, architects and builders visualised their buildings as being permanent, and did not make provisions for future changes.

In order to increase building sustainability, the design problem has to be extended to the whole life cycle of the building. This means including the operational and demolition phases as well.

2.2 LIFE CYCLE APPROACH

In order to extend the life cycle of buildings and their components, buildings should be designed by planning their service lives. In other words, the unit of design analysis regarding sustainable building should not be the building, but the use of this building over time, including environmental and economic impacts that the building design offers.(Figure 2.3 and 2.4) The key to sustainable design is therefore a life cycle design that integrates the requirements regarding efficient use of resources and market activities into all of a building's phases, from pre-building to construction, operation, and the post-building phase (Figure 2.3).

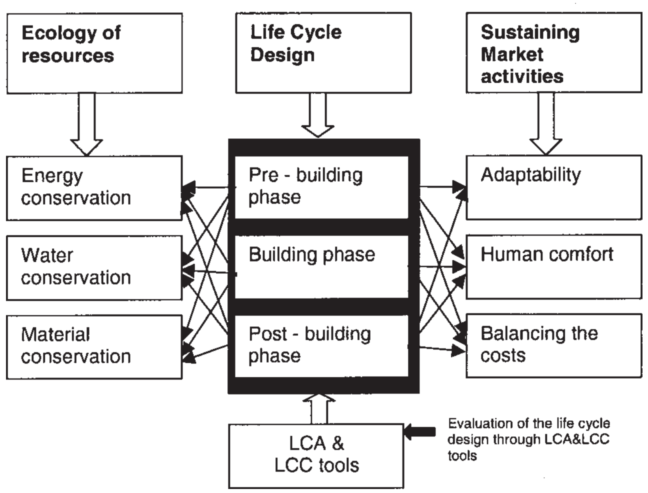
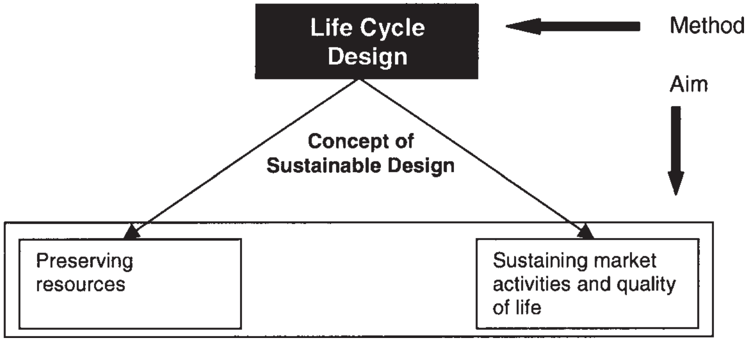


Figure 2.3: Integration of sustainability aspects into Life Cycle Design

Figure 2.4: The conceptual diagram of sustainable design is presented in the figure below.



A life cycle approach to design provides a methodology for analysing building processes and their impact on the environment. The principle tools developed to support such life cycle design are LCA (life cycle assessment) and LCC (life cycle cost). While LCA measures the impact of material use through all life cycle phases of building materials (Chapter 1), LCC focuses on building-related costs through a building's life cycle.

Life cycle assessment methods rely on prediction of when a building's elements and services deteriorate to a point where intervention is needed, and what the costs and environmental impacts of each intervention are. These methods can therefore also be used to provide an understanding of the environmental and economic benefits of a design for disassembly approach.

In order to understand the economic benefits of design for disassembly, one needs to compare estimates for traditional disposal with deconstruction costs. If one knows labour costs and disposal costs, then disposal costs can be compared with deconstruction costs, with adjustments for avoided purchase costs of new materials and resale/tax benefits of the reused materials. Examples of deconstruction projects in cities such as Los Angeles and Chicago illustrate that deconstruction of buildings that have valuable materials such as stone, aluminium, and hardwood can be profitable on small-scale projects. (Green Building 2005) (Waste Mach 2005)

Assessment of environmental benefits is related to many more factors than assessment of economic benefits. Manufacturing processes affect the degree of environmental impact prevented. The energy used and the energy sources for manufacturing has an important affect on environmental impact. The distance travelled between raw material extraction, fabrication, and end-use can improve or reduce the benefits.
The assumption in this research is that the number of changing sequences of building components will play a key role in achieving environmental and economic benefits of design for disassembly.

Until recently, investors considered that most financial risk occurs during the construction phase. Cost during construction can be affected by unexpected ground conditions, inclement weather, labour and material shortages, time overruns, defects, and faulty budgeting. (Clift 2003) *However*, investors who fund long-term projects realise there is even greater uncertainty in the operational phases of buildings. The lack of understanding of how buildings perform and how often and why they change, and where the need for intervention should occur, makes prediction of future costs unreliable. (Clift 2003)
The main discussion within this chapter relates to *analysis* of market activities and their influence on LCC and principles of sustainability.

2.3 "THE WORLD IS ON THE MOVE"

Very often buildings are seen as finished and permanent structures. They are carefully designed around short-term predictions of building use.
However, there can be no doubt that society is passing through a period of great change, and current predictions no longer favour short-term solutions.

"The world is on the move, was the conclusion of the forum and workshop "Five minutes city - Architecture and {im}mobility which was organised and held at the Berlage Institute (Berlage Institute 2002) in collaboration with the "Institut Francais

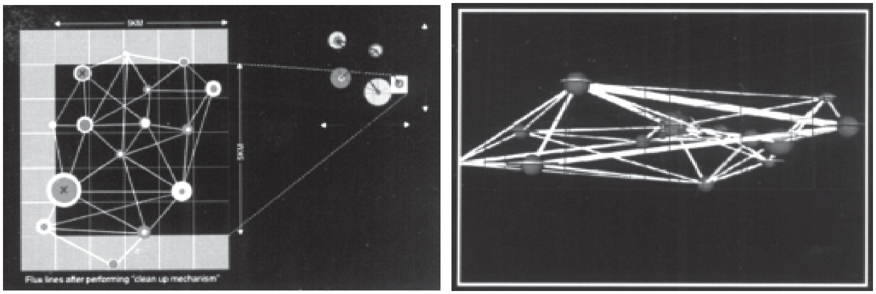


Figure 2.5: Expansion of the communication network (Berlage Institute 2002)

d'Architecture" (Paris) and the "Fundacio Mies van der Rohe" (Barcelona). The forum defined the state of today's developments through the following statement:" We communicate and travel faster, further, and migrate more times in our lives. This desires access. Access requires physical improvement that has dramatic implications on architecture. It also demands political and societal flexibility -in planning, real estate, urbanism and architecture. It requires changeable buildings, changeable urbanism and changeable real estate. Such a package can turn the world into an exhilarating, accelerating space." (Figure 2.5)

In an era of globalisation, increased mobility, and technological changes, businesses are growing and shrinking over night. Company strategies are changing towards maximal flexibility and decentralisation, in order to cope with fluctuating markets. Dynamical organisational structures developed in response to these changes require that environments be well suited to data processing, rather than be large permanent structures.

The Dutch Government has developed a number of nucleus offices in four big cities in the Netherlands, which are positioned at the crossroads of main communication routes. These nuclei have high tech communication facilities, and are connected to one data network. The main concept behind this is that employees are not bound by physical location. They can use these nuclei as working stations, by plugging into the main network infrastructure using laptops when needed, and by doing their normal work far away from headquarters.

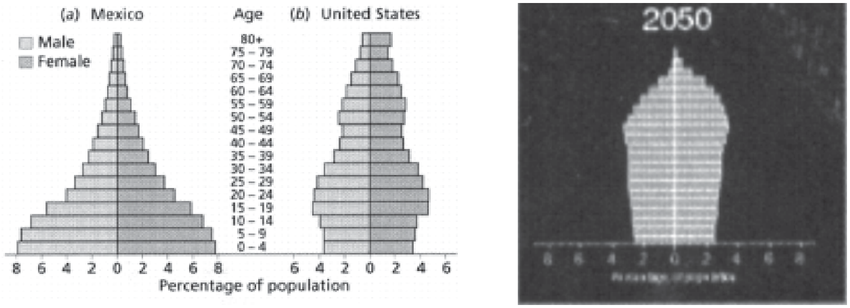
Furthermore lifestyles are changing due to the shift from fixed to mobile working stations, through workers working at home. This brings demands for greater diversity and changeability in the housing market.

Figure 2.6 Movable office, Germany 2000

Observers of current and future trends predict that the nature of working and living will change so drastically, and the scope expand so greatly that we will soon be faced with completely new building structures.
Present-day concerns for static objects will be replaced by concern for relationships. Shelters will no longer be static objects but dynamic objects sheltering and enhancing human events. Accommodation will be responsive, ever -changing and ever -adjusting. (Richard Rogers)

2.3.1 Scope and scale of change

The scope and scale of change of modern society can be seen in the demographic structure of global societies. For example in the 1950's the housing market was dominated by single-family homes with no reason seen to change the traditional way of designing houses. However, since the 1960's the position of buyers has increased and the traditional family has accounted in some western countries for only 17% - 20% of all family types (Friedman at all 1997) (Diagram 2.2). Today we could say that almost one quarter of all clients looking to buy a house, are singles or families.
Taking into account the transformation of the population pyramid, which is expected to change in a relatively short time, the housing market will continue to change. It is expected that by the year 2050 it will be dominated by a population older than 60 years. At the same time world population will have doubled. (Diagram 2.1)
Together with population growth, there is increase in mobility, which results in a increased migration. There are more than 150 million migrants worldwide. (Figure 2.7)



Diagram, 2.1: Population pyramid (Berlage Institute 2002)

Figure 2.7: Migration flow chart (Berlage Institute 2002)

Due to increased mobility the interpretation of place is changing. We do not live in one place any more and we adapt ourselves when moving around. All these aspects have great impact on the planning and design of our built environment.

Winy Maas wrote, " Classical urbanism cannot adequately handle the pace of society that so rapidly grows and changes. Recently realised urban centres are already inadequate to position new programs even before they are opened. Recently finished office buildings change ownership within three years after realisation. 20 year old suburbs change to accommodate new standards." (Berlage Institute 2002)
Considering this, cites and city components need to increase their " capacity to change " in order to accommodate future demands. Following the recent developments of the world metropolis, it is evident that the notion of change is accelerating. The landscape is shaped by expending programs. Programs follow investments and settle around new means of access. Programs create infrastructure that, in turn, create and attract program. This attracts even more traffic. Traffic jams must be resolved. The road becomes an artery, a bundle. Alternatives are created by enlarging the 'lace', creating a grid, a network. This is a seemingly endless process accelerating in itself ". (Figure 2.8)

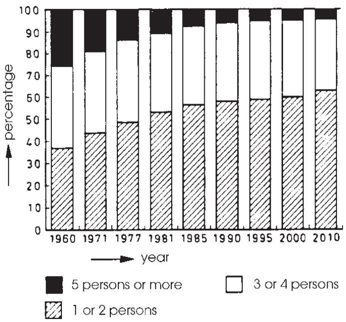


Diagram 2.2: Growth of the size of family in the period 1960-2010 (sl van TUD 90)

The question emerged: Can we plan for such a future? Can we suggest a city with a lighter behaviour in order to adapt itself? Can that not create a lighter form of urbanism that is more dominated by temporally, changeability, flexibility and accommodation than by eternity and monumentality? (Berlage institute 2002)

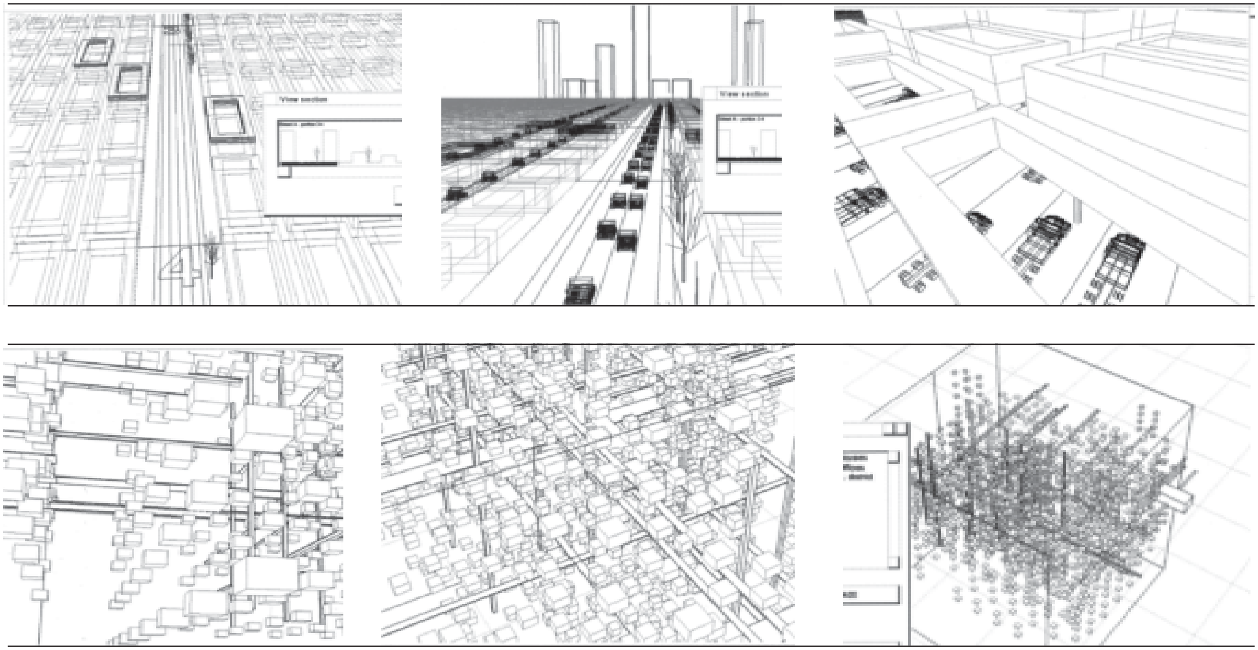


Figure 2.8: Acceleration of change imposes different construction, exploitation and developing patterns on the built environment(Berlage Institute2002)

The acceleration of change spreads from the city level to the building level. Recent research done by one of the biggest housing corporations in Amsterdam illustrates that the recurrence of changing sequences in dwellings is increasing. Dwellings whose design life is 50 years begin to change within three years. On average, the whole dwelling is transformed within 25 years (Figure 2.9).

It is expected that the pulse of change will accelerate even further in the near

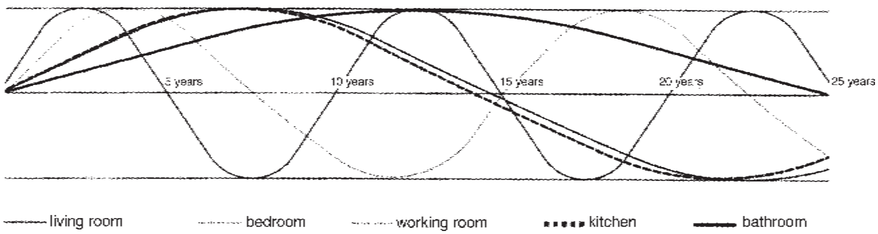


Figure 2.9: The pulse of change in dwellings (Rigo1999)

future.

Following today's trends of fast-cycling market changes, it becomes very difficult to predict future scenarios for the use of buildings. The uncertainty spreads not only to the question of how dwellings will be functionally organised, but whether they will be dwellings, schools, or something else after 10 or 15 years.

According to the above research, in about 73% of cases the initial spatial organisation of buildings does not meet user needs.(Table 2.1)

Table 2.1: Interest of different age groups in transformation of their dwellings by use of flexible system (Rigo99)

age	yes	maybe	no
until 31 years	86%	0%	14%
31 - 45 years	77%	16%	4%
45 - 55 years	73%	7%	20%
55 - 65 years	63%	25%	13%
more than 65 years	33%	42%	25%
Total	73%	0%	14%

Furthermore, 30% of families living in these dwellings would like to move because they cannot adjust existing dwellings to their needs. Another 45% would like to stay if the dwellings could be adapted to their needs. Table 2.2 shows the parts of the building that are frequently changed by tenants.

Table 2.2: Reasons why tenants need changes to their dwellings (Rigo99)

Reasons	Wall removed	Wall replaced	Wall add	Alternitive
To create more space	75%	74%	43%	19%
For aesthetic reasons	10%	0%	13%	13%
Changes in family	2%	0%	25%	9%
To have more light and sun	4%	0%	0%	3%
For more privacy	0%	0%	0%	9%
Because of the illness	2%			
Because of acoustics				3%
Because of hobbies			6%	
Because of children	1%			
Other	6%	26%	13%	44%
Total	100%	100%	100%	100%

Similar to trends in the housing market, today's economy forces businesses towards mobility and flexibility in order to survive accelerating shifts in local and global markets. Fluctuations in office markets can be best seen in the chart representing

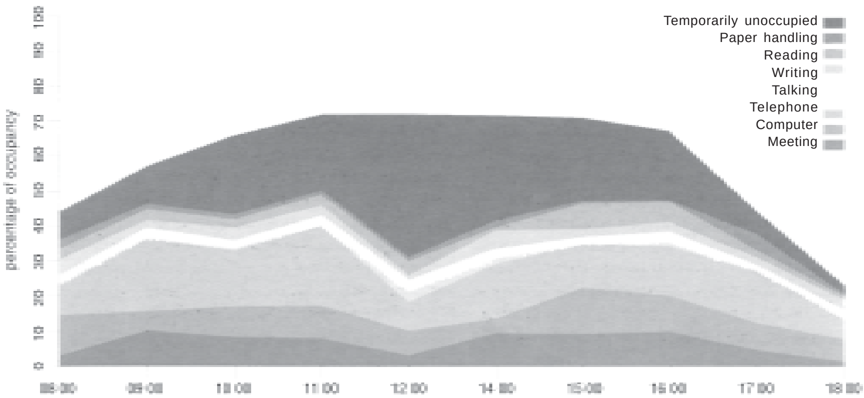
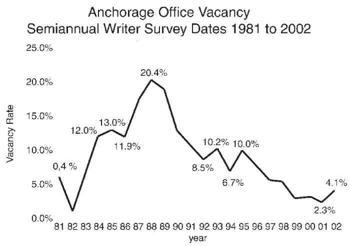


Figure 2.10: Diagram illustrates the efficiency of use of space within office buildings. Due to the frequant changes office buildings often deal with unocupied space. Offices are not designed for efficient adaptation to the new requirements (Duffy 1998)



Figures 2.11: office vacancy rents

office vacancy rents, which constantly shift according to market conditions. (Figure 2.11) Flexibility has been an important issue in office design for a long time. Changing rates in public buildings are more frequent than in housing. These changes are not only related to organisational changes, but also to the maintenance, and keeping abreast of new technical requirements. For example, technical installations in hospitals should be renewed after 10-15 years. This is often related to major structural changes, and demolition, in parts of the building. Duffy warned that in the changing work place, only those speculative office buildings designed with the benefit of systematic organisational thinking would survive commercially. "Only those corporate users who have the imagination to link the organisational development to design imagination are likely to procure buildings that will escape obsolescence." (Duffy changing workplace 94)

As a consequence buildings' flexibility and serviceability will be considered increasingly as a business resource, next to human talents, capital, technology, and information. (Anh and Wyatt 1999)

Offices construction	
	Mil.euro
new offices	5706
reconstruction	1996
Maintenance	5068

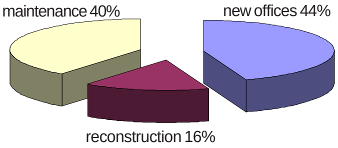


Figure 2.12: Division of investment costs in office sector for the period from 1998-2002 (Damen 1998)

Housing construction	
	Mil.euro
new construction	6659
reconstruction	3607
maintenance	2655

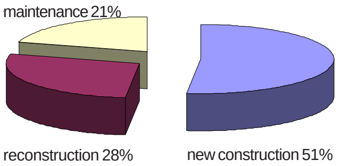


Figure 2.13: Division of investment costs in housing sector for the period 1998-2002 (Damen 1998)

2.4 CONSTRUCTION ACTIVITIES IN PUBLIC AND HOUSING SECTOR

The main characteristic of existing office buildings is that their spatial organization cannot accommodate new office types. The trend in the office market today is for office spaces that are often rented as independent units. Therefore, it is important that these building can be split into separate units. Another requirement on office buildings today is that they can easily mutate from one organisational concept to another.

Most existing office buildings cannot satisfy these requirements. Flexible partitioning is not possible without large amounts of lost space being created (Damen 99). Existing buildings have many communication and service spaces and many office concepts cannot be realised in them. (Figure 2.10) Furthermore, their spatial system is often fixed for one office typology.

Due to the individualisation and increase of supply on the housing market in Western Europe, the requirements of the housing market are similar to those in the office market. If dwellings cannot be adapted to their users, they will stay empty.

Most of the existing building stock does not have the capacity to transform. Therefore, they are subject to demolition and renovation. In this way, building production is mainly focused on replacement of old buildings by new construction and renovations. This can be seen in the data that represent yearly building production in the Netherlands. Table 2.3 gives an overview of governmental activities in relation to its real estate management, based on null, impulse and crimp scenarios. The activities are very dynamic regardless of the scenario, because of the inflexibility of existing building structures.

Table2.3: The government's estimation of its real estate activities given in m2 until 2010 based on three scenarios (Rijksgebouwdinst 1996)

Offices	Null scenario	Impulse scenario	Crimp scenario
New construction	250 - 750 000 m2	885 - 935 000 m2	200 000 m2
Reconstruction	70 - 520 000 m2	280 - 690 000 m2	168 000 m2
Give a way	600 - 1 000 000 m2	525 - 750 000 m2	525 000 m2

Table2.4: Building production in the housing sector for the period 1995-2010 ((Rijksgebouwdinst 1996)

Housing	Nr. of dwellings
New construction	750 000 - 1 100 000
Reconstruction	825 000
Demolition	127 500

An overview of the building production of dwellings for the period from 1995-2010 is given in a Table 2.4. These developments follow the trends in office buildings. If we analyse the costs of building production from 1998-2002 in the Netherlands, one realises that the dynamic of investments is divided in two almost equal parts between new construction on one side and maintenance and reconstruction on the other. (FIgure 2.12 and 2.13) This means that about 50% of investments in building construction are spent on adaptation and maintenance, which amounted to 3200 million Euros in 2002. (Damen 98)
It is also interesting to note that about 42% of new construction is due to the replacement of demolished buildings. This gives an indication of the dynamics of activities around building stock that is not designed to adapt to market requirements.

The key obstacles for successful transformation of buildings are often related to:

- Spatial inability to mutate from one use concept to another,
- inflexible load-bearing structure,
- inflexible installation systems that cannot easily adapt to different spatial typologies,
- lack of accessibility to the old installations,
- lack of space for the new installations, and
- fixed integration between load-bearing and non load-bearing parts of the building.

Taking into account the yearly construction and demolition activities presented above, one realises that the crucial problem of today's building construction is that buildings are made such that alterations to them lead to the demolition of parts of a building, or even to their whole structure. The main reason for this is that building materials are integrated in one closed and dependent structure, which does not allow alterations and disassembly.
The inability to remove and exchange building systems and their components results not only in significant energy 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.

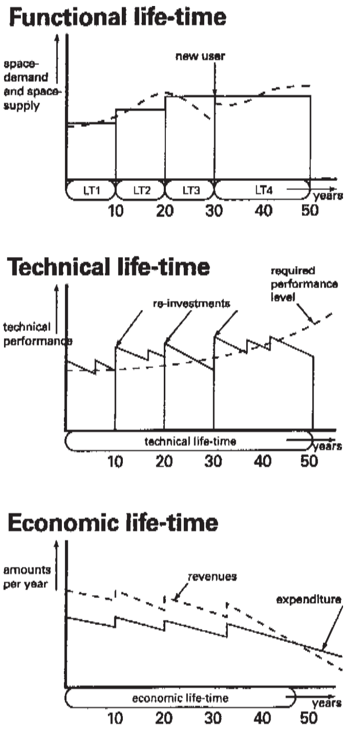


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Figure 2.14: Functional,technical and economic life time (Jong1997)

2.5 MARKET ECONOMY AND DEMAND FOR FLEXIBILITY

The case for the Life Cycle Approach

The need for change is a market phenomenon that began at the turn of 20th century. Flexibility and freedom of choice for the user has become a slogan of many building owners and developers. However, buildings are not designed for flexibility.

Conventionally, the technical and functional service life of a modern building is approximately 50 years. Yet, today buildings with an age of 15 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. In order to extend the life cycle of the building and its components, the building should be designed focusing on the building as an economic and sustainable solution for a desired use strategy over time. This means that the unit of design analysis is not the building it is the use of the building over time.

Having this in mind De Jong explored the relationship between functional, technical, and economic life cycle shown, in Figure 2.14

Functional life span is related to the use of the building while the technical life span is determined by its technical state. The service life of the building is a result of the balance between supply (technical– life span) and demand (functional life span). In some case, the economic life span is also seen as a result of this balance between supply and demand (Hermans 1995). This implies that the economic life span ends when the functional requirements are not met by the technical specifications. This causes economic action such as investment in replacement of components, or investment in demolition of structure.

The top graph in the figure 2.14 shows the growth and decline of a users organisation. The organisation was changed two times over 30 years. In relation to this, the second graph shows the technical performance required for these changes.

The technical life is a life span within which the building meets the technical performance requirements in a given maintenance strategy. The required

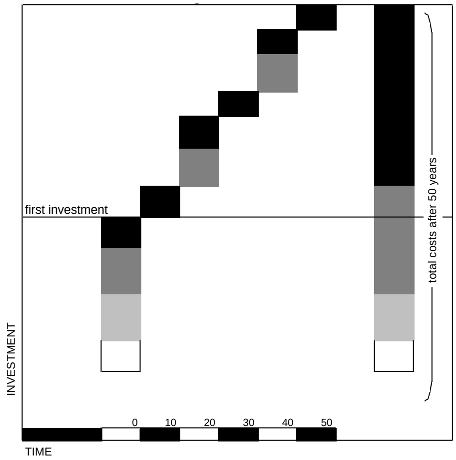


Diagram 2.3: Conventional view of building cost. Diagram showing the total investment after 50 years
Over 50 years adaptation of building costs three time more than the original building

Scenario
major adjustments every 20 years

division of costs

- partitioning, equipment and finishing every 10 years
- installations every 15-20 years
- structure and envelope every 50 years
- location

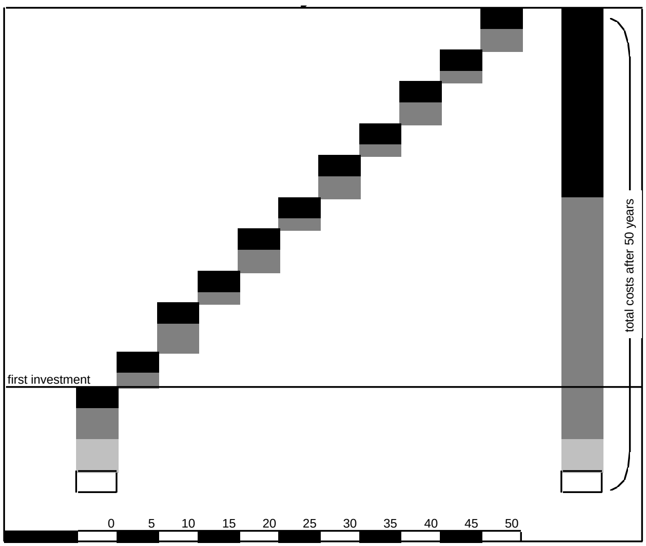


Diagram 2.4: Conventional view of building costs. Diagram shows the total investment after 50 years
Over 50 years adaptation of building costs four to five times more than the original building

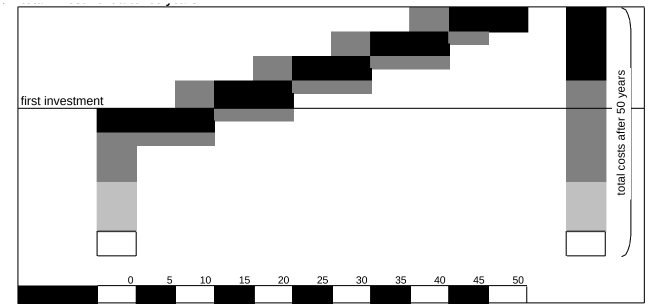
Scenario
spatial adjustments every 5 years
adjustment of installation technique every 10 years (adjustment scenario predicted by the housing corporation)

division of costs

- partitioning, equipment and finishing every 5 years
- installations every 10 years
- structure and envelope every 50 years
- location

Diagram 2.5:The new view of building costs.Diagram shows the total investment after 50 years taking into account the design for disassembly aproach.
Over 50 years adaptation of building costs half of the original building

Scenario
spatial adjustments every 5 years adjustment of installation technique every 10 years (adjustment scenario predicted by the housing corporation)



division of costs
- partitioning, equipment and finishing every 5 years
- installations every 10 years
- structure and envelope every 50 years
- location

performance not only depends on functional fitness for use requirements but also heavily on regulations.
The third graph shows the economic life of a building. Economic life is the time span within which the building meets the return on investment criteria of the owner. (Ang & Wyatt) Each time functional and technical changes are made, the revenue and expenditure graph changes. Taking into account conventional building methods, the number of changes has an influence on total economic life. This means that besides operational costs which have an influence on total life cycle costs primarily thorough energy use, construction methods are equally important when it comes to the Life Cycle Costing of one building, and its environmental impact.
Decisions made early in the design process can have significant influence on total life cycle costs. Building orientation influences the amount of solar heat gain and level of cooling required; façade design influences the costs of access for cleaning and repairs; integration of building components influences the cost for access, maintenance and replaceability of components and so on. Life cycle calculations are useful when assessing whether higher initial costs are profitable in the long run.

Duffy analysed the cumulative building costs of office buildings. He concluded that over 50 years, changes within the building cost three times more than the original building. (Diagram 2.3) Duffy explains that in conventional office buildings the expenditure on structure is on average overwhelmed by the cumulative financial consequences of three generations of services and ten generations of space plan changes. This is the map of the money in the life of a building. Such assessment of costs were based on market conditions 20 years ago. However, today’s market conditions are somewhat more dynamic, resulting in space plan changes every 3-5 years. Space plan changes affects most of installation’s distribution network while the general installations are changed within 10-15 years. Cumulative building costs based on current market conditions are shown in Diagram 2.4.

Both diagrams are based on existing building practice within which every time that changes take place, parts of the building are demolished and new ones are built. The same is true for maintenance, which also influences capital value and accordingly, total investment costs. (Diagram 2.6) According to Brand, due to deterioration and obsolescence, a building’s capital value is reduced by almost half, twenty years after construction. The general approach of building owners and investors is “if repairs cost half of the value of the building, the building is demolished. In a building economy well -maintained buildings are bound to hold their rental and sale value better than the usual frapped-out structures.” (Brand 1995).

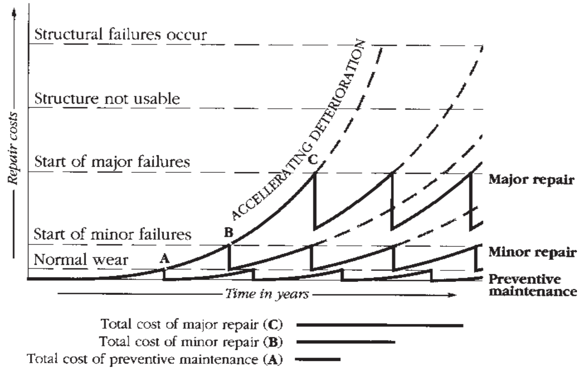


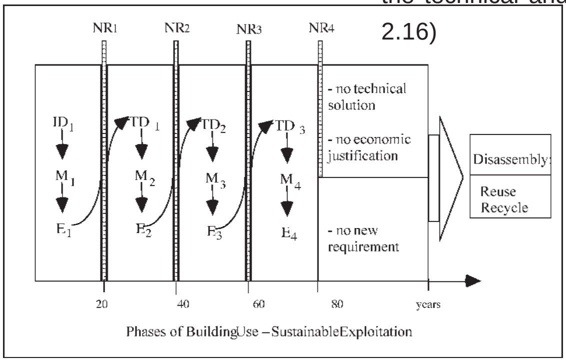
Diagram 2.6: Maintenance schedule vrs total investment costs (Brand 1995)

But if one thinks in terms of design for disassembly that would a provide solid maintenance strategy by easy accessibility and exchangeability as well as reuse of building components, then the cumulative building costs could be reduced two to three times (diagram 2.5).

Some developers in the Netherlands have already recognised the economic potential of such a strategy. One example is Wereldhaven in the Netherlands which recently developed a project “Office building XX” with a design life of 20 years, and whose components are recyclable and reusable. According to director Verweij, the motivation for such a project is because that developers are confronted with raising demolition costs, and that sections of a building have to be replaced after ten years. These discarded materials no longer have a function, but are not yet worn out. Verweij in an interview with PhD students stated this situation costs a lot of money. For this reason, the objective of the experimental project XX was “if materials no longer have a function, they should be reused or recycled.” Such a situation requires new concepts and methods of construction that allow economically and environmentally efficient transformations of built structures and their components.

2.6 TECHNICAL VERSUS SPATIAL AND ECONOMIC SYSTEM

Buildings are designed to stand for 50-75 years. Yet generally speaking the economical duration of one phase in the use of a building is shorter than the technical life span of most of its components. Every new phase in use of a building implies new requirements and spatial organisation. This involves changes to the building. This means that after each use phase, an assessment should be made to indicate whether the building is suitable for its new requirements; if not, what the technical and economic consequences related to its adaptation are. (Figure 2.16)



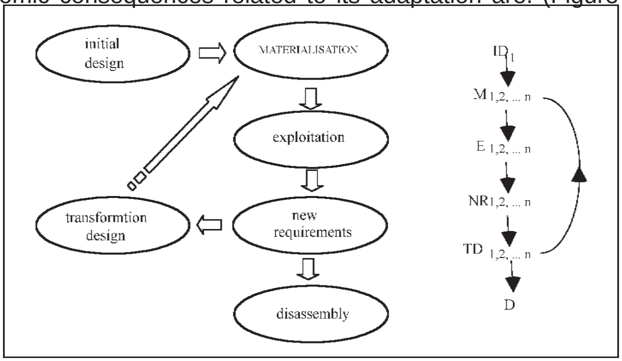


Figure 2.15: Number of sequences in building use

The diagram in Figure 2.15 represents the moments of decision-making regarding the further use of the building. If there is no suitable technical solution or economic justification for changes based on new requirements, the building reaches the end of its life cycle before the end of its design life cycle.

Figure 2.15 right illustrates the life cycle of a building in context of sustainable design, which depends on repetitive sequences (from materialisation to transformation design). The number of loops that can be made between the design and demolition/disassembly phases of the building depends on the technical and spatial characteristics of the structure. In other words, it depends on the spatial and technical flexibility of the structure.

Spatial systems cannot be observed independently of technical systems, since mutations of space are directly related to the technical composition of a building. Rearrangement of spatial systems is difficult to achieve if the interfaces between the components brought together to create a particular spatial system, are not designed for exchangeability.

Space transformation happens during the operations phase of the building. It can be forced by organisational changes within the company or by market changes that require enlargement or reduction of office units. Therefore, indicators of spatial flexibility can be defined as:

- Extendibility (enlargement of the space),
- partitioning (rearrangement of space units),
- multi-functionality (rearrangement within space units), and
- functional mutation (mutation from one function to another).

Technical flexibility is related to the ability of building components and systems to be easily replaced, displaced, reconfigured, reused, and recycled.

The indicators of technical flexibility are:

- Accessibility,
- replaceability,
- reconfiguring, and
- separation.

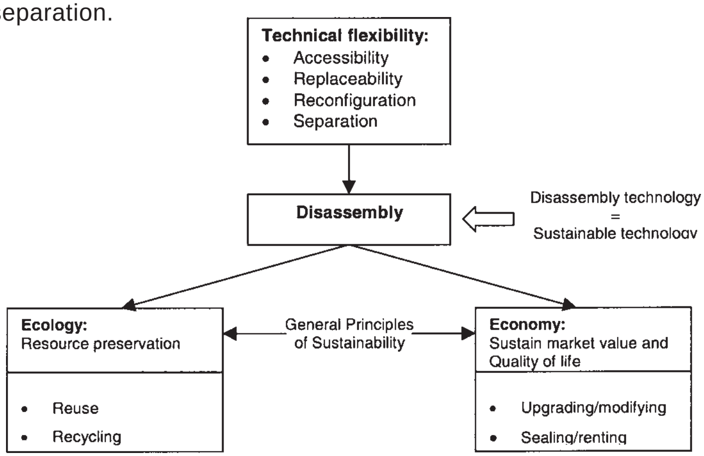


Figure 2.16: Relevance of design for Disassembly

In order to accomplish this, building configuration should be designed for disassembly. In that respect technical flexibility with associated disassembly can be seen as the key to sustainable construction. (Figure 2.16)

Technical flexibility makes sustainable building possible not only by reuse and recycling possibility but also by making building adaptable to follow trends and technological developments. It makes upgrading of building systems (to keep up to the standards) possible.

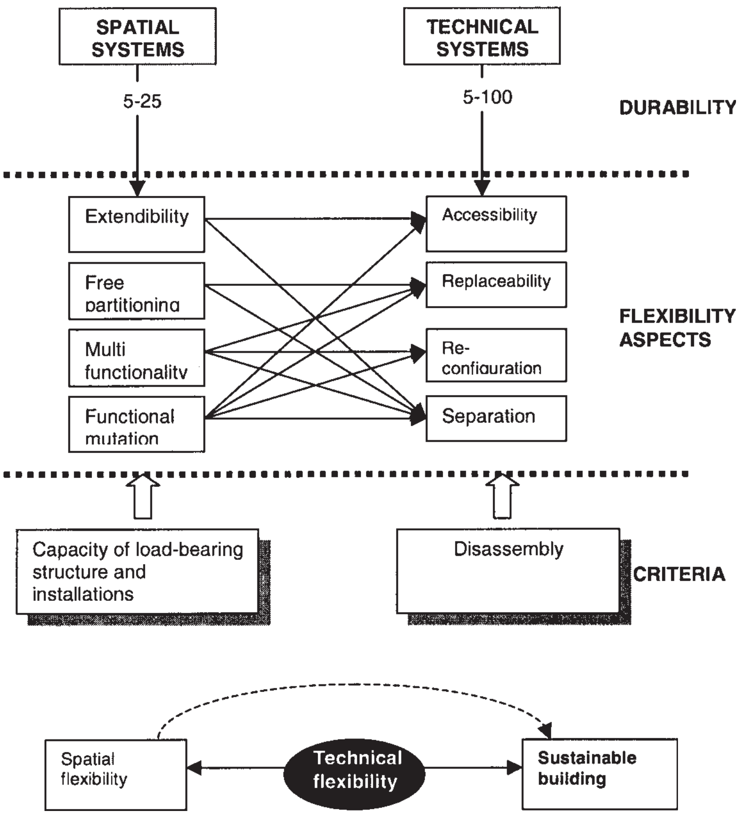


Figure 2.17 Dependences between spatial and technical flexibility

There is natural interdependency between technical flexibility and spatial flexibility and they cannot be isolated from each other. Every change within the space has consequences for the technical systems of the building, and vice versa. (Figure 2.17)

To show the potential of spatial and technical flexibility, a case that illustrates reuse of an office building in London is discussed below.
A sixteen-floor office building in central London had to be adapted in order to operate it as a viable office building. Total demolition and rebuilding was an option because a narrow plan and a floor-to-floor height of 3.2 m was not sufficient to accommodate the increased service hardware required by modern information technologies. The architects Sheppard Robson carried out feasibility studies into the building's potential future use. After studies of the structural capacity and façade assembly, the architects, together with the structural and mechanical engineers Ove Arup and Partners, devised a strategy of retaining the existing building skeleton and upgrading it by adding a clip-on service zone to the building. By introduction of the vertical service zone, the floor plan is extended and extra space is created for the services under the clip-on console. It turned out to be possible to increase the net-lettable floor area by 20% after stripping out the floor screeds, half-height block-work wall, and massive double story height rooftop, and by replacing them with a lightweight structure. (A. Brookes 92) (Figure 2.18)
Thanks to such a solution, a 27-year-old building that was supposed to be demolished — although its materials could last probably 50-75 years — came into another life cycle. Such prevention of demolition gives best results in the reduction of waste, use of raw materials, and energy. At the same time, it has significant economic advantages due to the elimination of demolition and landfill costs, as well as building costs related to the construction of the new structure.

2.7 NEED FOR NEW CONSTRUCTION METHODS DUE TO THE GROWING DISPROPORTION BETWEEN TECHNICAL AND USE LIFE CYCLES

As discussed in the previous section, buildings represent integration of spatial and technical systems. Although the technical systems of a building are there to support spatial systems, in conventional buildings technical systems dominate spatial systems due to their fixed configurations. In other words, every spatial

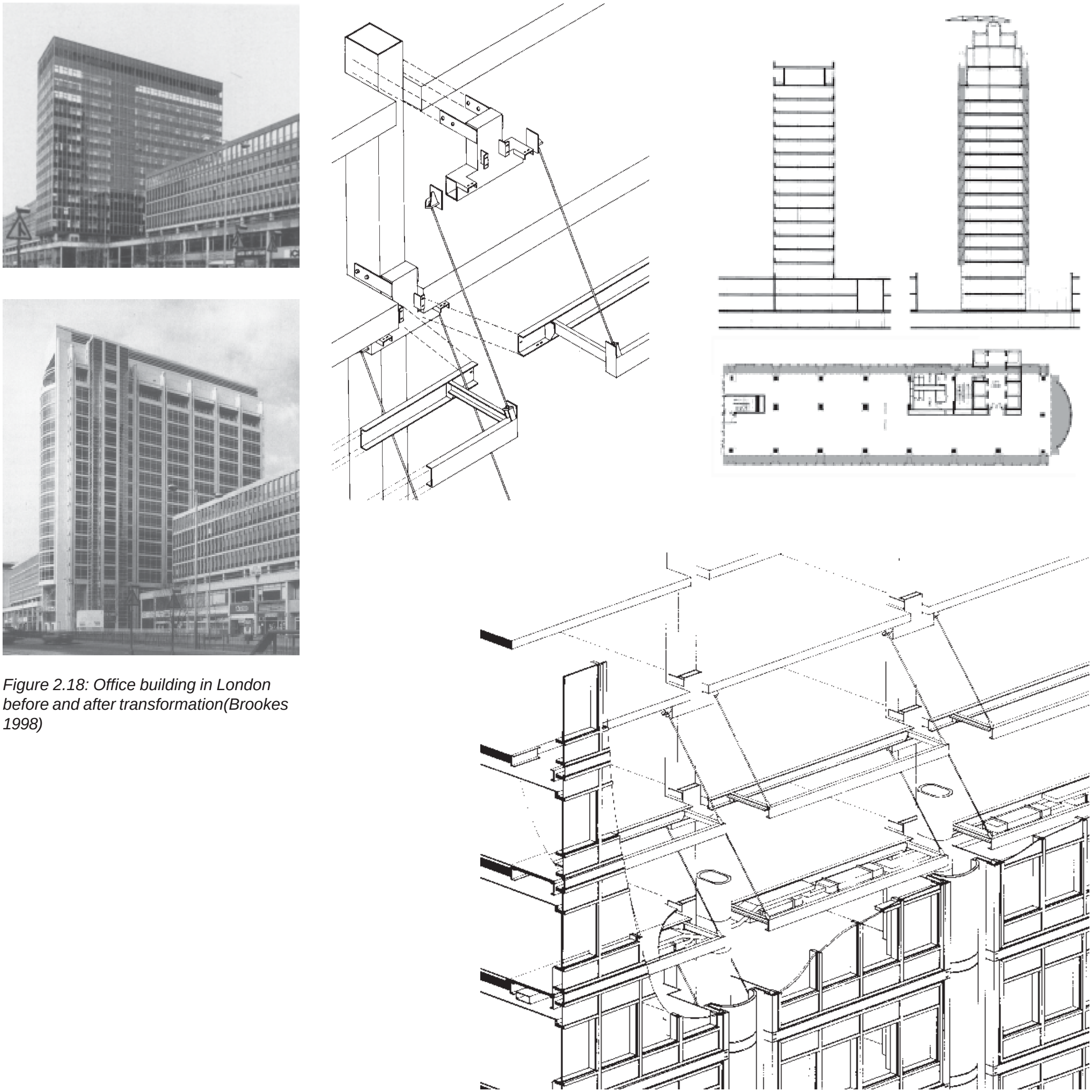
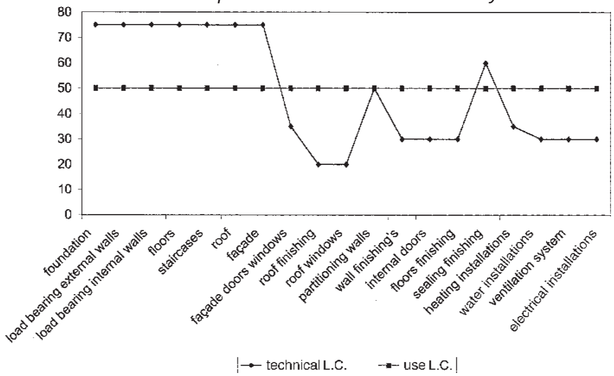


Figure 2.18: Office building in London before and after transformation(Brookes 1998)

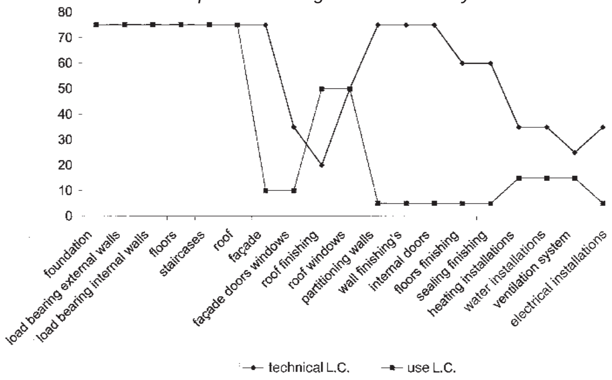
change is related to the economic and environmental costs due to the static nature of the configuration of technical systems. Thus, if spatial systems have shorter life cycle than technical systems, the demolition of materials will take place. A similar approach can be applied to building systems. If the use life cycle of a building component is shorter than the technical life cycle of a building component, then the component will be disposed. Decades ago this was not seen as a problem, since the use life cycle of building components or life cycle of special systems was more or less equal to the technical life cycle of the building. The focus of design was more on durability of the technical systems and maintenance strategies, rather than on the durability of use phases. However, circumstances have changed. Due to the ever-increasing mobility of people, services, and the development of virtual networks, static use scenarios for built environments are disappearing. This means that use requirements, and thus functional and spatial systems, are changing much faster than the materials used to provide these systems. Since current technical systems do not have the potential for disassembly, this results in increased materials, energy use, and waste production. For that reason, fixed technical configurations that cannot be replaced, reused, reconfigured, or recycled are no longer feasible and are becoming a burdento society.

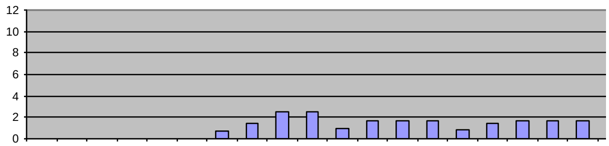
Due to ever-shorter use life cycle of components, the disproportion between use and technical life cycle is rapidly increasing. At the same time, the changing rate of building components is increasing as well. This can be illustrated through a life cycle coordination diagram that indicates the difference between the technical and use life cycle of components that have long use life cycle (Figure 2.19 left) and component that have short use life cycle (Figure 2.19 right). The difference between use and technical life cycle of one component depends on the use scenario of the building on one hand (which defines the changing rate of the spatial system) and the durability of its used materials on the other. Scenario 1 in Figure 2.19 left illustrates use life cycle of all building components being 50 years, with their technical durability. The main operational issue within this building is maintenance and replaceability of components that have a shorter technical life cycle than 50 years. Most components in these structures have no reuse potential.

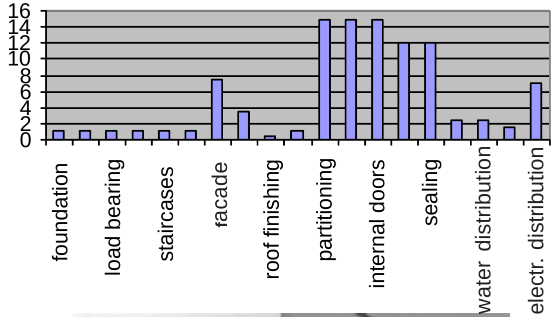
Scenario 1: technical life cycle of building components is shorter than use life cycle



Scenario2: technical life cycle of building components is longer than use life cycle







Scenario 1

Scenario 2

Figure 2.19 Use life cycle versus technical life cycle
Scenario 1: Conventional aproach to housing and reuse potential of materials.

Scenario 2: State of the art regarding the dynamics of change(Rigo 99) and Reuse potential of materials

Figure 2.19 right is a scenario based on recent market research in housing, which indicates much shorter phases in the use of dwellings. It has been already suggested in this chapter that the change of use patterns begins already after five years. These changing patterns affect durability of walls, finishing, installation services, doors, windows, and façade , as they are associated with a shorter use life cycle.

Comparison of these two scenarios show that shorter use life cycle involves a higher changing rate for materials. This means that materials have a greater reuse potential.
For example, an element whose technical life cycle is 50 years and whose use life cycle is five years, can be reused ten times. If this reuse potential is not exploited, then greater number of changing rates of spatial systems results in increased material use, embodied energy, and waste production. Table 2.5 gives an indication of the reuse potential within conventional housing projects. It shows that conventional buildings are not designed for reuse of their components.

no.	relations		disassembly	demolition	reuse	recycle	waste in disassembly	reuse potential
1	connstruction-ffacade		partial	yes	partial	partial	80%	
2	connstruction install..		no	yes	no	partial	95%	
3	construction-finnishing		no	yes	no	partial	100%	
4	construction part.walls		no	yes	no	partial	95%	
5	construction-roof		partial	no	no	partial	95%	
6	roof-roof finnishing		no	yes	no	partial	100%	
7	wals - install		no	yes	no	partial	95%	
8	floor-install		no	yes	no	partial	100%	

Table 2.5: Reuse potential within conventional housing project

2.7.1 DfD and economic benefits

In order to indicate economic benefits of a design strategy that encourages disassembly and reuse of building components, a case of a hospital research centre in Leiden is presented.
The LUMC Research Centre in Leiden was given an award by the Dutch government for Industrial Flexible Demountable (IFD) Buildings. The building is a research centre for the main hospital in Leiden, which has very dynamic changing sequences in its use of laboratory units.
The architectural office EGM from Rotterdam provided a solution for the following use scenarios during the design process:
- extension and shrinking of research departments
- adjustments to the norms
- addition of the new research units for a specific project
- modifications of the units

Such requirements were accomplished by reserving extra space for services, and the design of dismountable systems. The Life Cycle Costs of this project indicate that although the initial investment costs are higher, return on investment can be report of the IFD projects).

In order to answer such requirements the following measures were taken:

- additional space for air-handling units	Euro 289.800,-
- additional space for the main air duct	Euro 515.200,-
- additional space for sub-ducts distributed on seven levels	Euro 289.800,-
- additional space for get-together box	Euro 177.100,-
Subtotal	Euro1.271.900,-

Measures in respect with building technology aspects:

- additional costs for demountable system walls	Euro 174.150,-
- additional costs for extra parts to standard modules	Euro 288.720,-
- additional costs for extra escape routes	Euro 465.860,-
- additional costs for the extra floor system	Euro 391.950,-
- adaptation of the laboratory furniture	Euro 678.452,-

-	materials for sub-ducts	Euro 844.855,-
	Subtotal	Euro 2.843.987,-

Measures related to the installation techniques:

-	strengthening of air ducts	Euro 125.000,-
-	strengthening of pipeline that cools offices	Euro 100.000,-
-	strengthening of pipes that heat offices	Euro 100.000,-
-	additional floor boxes in standard laboratories	Euro 55.000,-
-	rail system in sub-ducts	Euro 125.000,-
-	light switching system	Euro 220.000,-
-	reserve in data and phone installations	Euro 220.000,-
	Subtotal	Euro 975.000,-
	Total	Euro 5.090.887,-

The report concluded that estimated additional costs with respect to flexibility and disassembly are Euro 5.090.887. This is 8% of the total building costs.

In order to evaluate the potential of IFD technology, the research compared costs of changes within a traditionally built research centre compared with costs of changes in a flexible research centre. One renovation within a traditionally built research centre costs Euro 54.943,14. Opposite to this one renovation within a flexible research centre would cost Euro 3.868,24. There is a difference of euro 51.740,90 per renovation. Savings within a flexible research centre during renovation amounts to Euro 25.500, per module that must be changed. Each module has 25m2. This means that Euro 1202, per m2 can be saved during renovation. Additional investment in the flexible research centre is Euro 5.090.887. In order to return this investment within 15% some 332 m2 should be changed per year.

On average, 10% of the use surface within the LUMC building complex is renovated each year. The floor service of one flexible research centre is 2598 m2. Out of this, 1446 m2 is net usable space. This means there are 8676 m2 of net usable space on six floors. 10% of 8676 m2 is 867,6 m2. This is 2,5 times more than the surface needed to have a return on investment within 15 years.

In other words, if 10% of the space within the research centre is renovated each year, the investment return would be 6 years.

For a building that lasts 30 years, 25 million euro would be saved during the adaptation phases. Such savings are possible thanks to an initial additional investment of 5 million Euros. (Source: Evaluation of the IFD Projects, 2005)

Chapter 3
A systematic approach to design of the building transformation

Building is not something you finish.
Building is something you start
Brand 1995

INTRODUCTION

This chapter focuses on disassembly as the catalyst of transformation for spatial, structural, and material levels of the building. Design for disassembly is seen as a link between building technology and sustainable development. It is concluded that a transformation capacity that relies on high disassembly potential of structures results in higher sustainability.

This chapter deals with a number of questions that frame the new design strategy. Two main questions are when and where does disassembly take place? These questions are explored using a theory of levels that recognises that different parts of a building structure have different life cycles. The first step towards design for change is to decouple independent levels that have different degrees of durability. Further to this, questions as: how can independent levels be recognised, and how can their physical independence be provided will be discussed. These questions have been previously discussed.

Studies that deal with the transformation of the built environment in the past decades have had different interpretations of time levels. Some studies have seen it through functions, which have different life cycles, others through the levels of responsibility or technique.

However, this research argues that it is the levels of technical composition, which deal with integration of functional and physical levels that play an important role within transformable structures. Every building represents the integration of functional and physical levels. Although physical levels are there mainly to materialise certain functions, the natural interdependency between function and materials has become a bottleneck for transformable structures. The life cycle of one set of function-material relationships becomes shortened because of rapid functional change. Due to the nature of technical composition, it is often the case that durability of functional levels determines the durability of physical levels. This research suggests that when the life cycle of physical levels becomes independent of the life cycle of functional levels, the durability of technical systems and their materials can be extended. This is the main goal of sustainable construction.

3.1 TRANSFORMATION

In previous chapters, problems that relate use of materials and market conditions were discussed in the context of sustainable building. It has been suggested that the disassembly concept can provide more efficient material use, and that its technologies could answer market requirements of the 21st century (providing economic and environmental benefits). Moreover, such a concept would help users of buildings to adapt them easier to their expectations. In order to understand the nature of disassembly, it is important to realise that disassembly is an essential part of the transformation concept. In other words, the built environment can become sustainable if its transformation is based on disassembly and not on demolition processes. Transformation in the built environment is the result of the human need to adjust physical surroundings to human activities, using available technologies. Transformation suggests dynamic behaviours that result in transformations from one form into another. This can involve spatial, structural, or material transformation. Habraken pointed out in his book ‘Transformation of the Site’ “Cities rise and fall. Streets are broadened. Buildings are taken down and new ones go up. Rooms are redecorated. Porches are added, doors painted, holes knocked into walls, and windows walled in. The site is constantly subject to transformation.”(Figure 3.01)

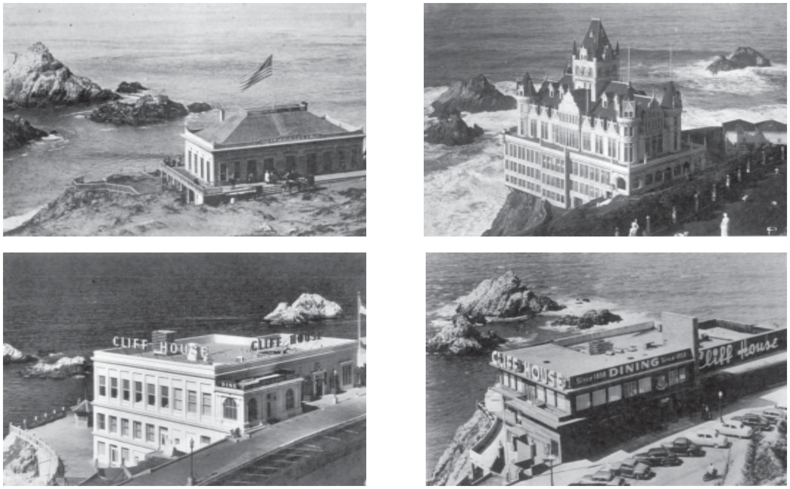


Figure 3.01: Transformation of one site during 50 years. (Brand 1995)

Furthermore, every building transformation is based on three main operations:

- Transformation by the elimination of the element,
- transformation by addition of the element, and
- transformation by relocation of the element (Habraken).

The conclusion from Chapter 1 is that these operations rely on technologies that depend on primitive, highly consuming industrial systems with little material recovery. Accordingly, in Chapter 2 market conditions were analysed. Due to high material and energy-consuming transformation processes, the increasing changing rate of buildings and pure maintenance strategies drastically increase the total life cycle costs of building. This has had also a big influence on investor's decisions to demolish structures much earlier than planned (in some cases just ten years after construction), and build new ones.

The world's economic system depends on increasing of consumption (which relies on the need for change); while the world's ecological system is in decline because of this consumption. If we do not think of ways to control this change, at a certain point the system could break.

Considering this, the main question of sustainable building is how to balance the environmental, socio-economic, and technological aspects of design. These relations were analysed using Steph's equation in chapter one. It has been concluded that a balance between the environment and highly dynamic human activities could be achieved by changing technologies, and by manufacturing products using cyclic processes. In other words, product and building structures should not be designed as static but as dynamic structures, which can be modified and their components easily recovered, reused, and recycled. Such concepts if applied on all levels of technical composition of building would allow for up cycling of materials, reconfiguration and reuse of components, systems, and buildings. Therefore, attention in future should be on development of design concepts that master the transformation of structures based on disassembly, such that elimination, addition, and relocation are not a bottleneck for a sustainable environment, but that the environment and society can benefit from these operations.

3.2 REMAKE – LEARNING FROM THE PAST

Before discussing this new approach, it is useful to look at attempts in the past aimed at flexibility and disassembly.
There are novel examples of buildings from the past that were designed for transformation. Industrial technology was used to achieve this, such that components could be exchanged, reused or recycled. Cedric Price was an architect who pursued the idea of flexible assemblage of independent components in the 1960's, through his conceptual drawings for the 'Fun Palace', 'Potteries Thinkbelt', and later through the realised project of the 'International Community Centre'.

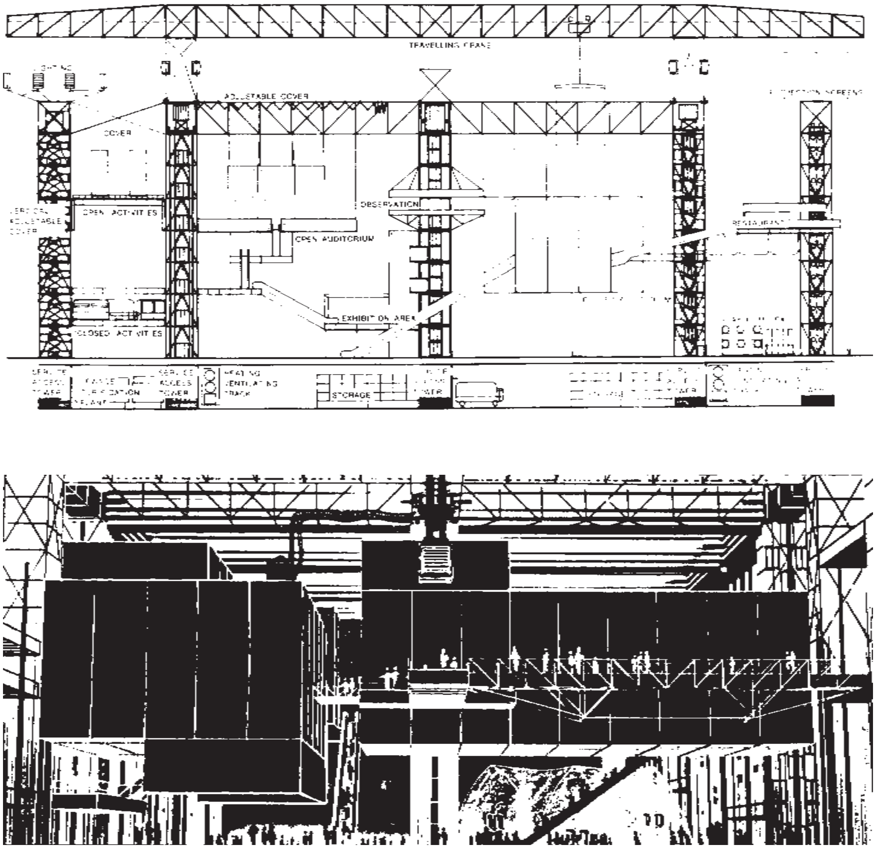


Figure 3.02: Fun Palace designed by Cederik Price 1961

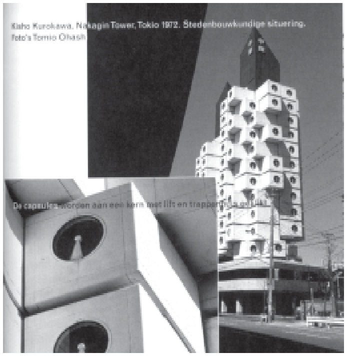


Figure 3.03: Above capsule house Japan, below hotel in Tokyo

His scheme for the Fun Palace was an inspirational work in the realm of adaptable buildings (Figure. 3.02). The concept was based on a large structural frame on which different units and components could be clicked on or off. The structure itself could be constantly changed and adapted to different needs by use of movable walls, roofs, and crane runways. The architecture was indeterminate, flexible, and driven by current technology.

As an architect particularly interested in lightweight structures and the idea that buildings should have a fixed, often short life spans, it was inevitable that he would build little, during a period when buildings were increasingly seen as solid, longlasting investments.

Through his designs, Price explored architecture's potential to nurture change, intellectual growth, and social development, rather than to offer a definitive aesthetic statement (Jeremy Melvin, August 15, 2003 The Guardian).

The 60's saw a major outpouring of experimental architectural design linked to the tensions of the Cold War and the dreary monotony of most new urban developments. Simultaneously, a number of avant-garde groups emerged around the world: Archigram in the UK, Metabolists in Japan, EAT (Experiments in Art and Architecture) in USA, UFO and Superstudio in Italy. Most of these groups set out to challenge the conventional view of architecture and experimented with new materials and concepts using adaptability as a driving force for innovation.

Archigram's work was perhaps the most widely publicised, and others have subsequently explored most of their ideas. Their Plug-in City, for example, was based on the development of the urban framework that recognises the need for

Figure 3.04: Walking city – Archigram 1964

long term planning of infrastructure, which will provide continuity of place and the short-term use of different city components such as houses, hotels, offices, industry etc. In the Plug-in City project, the whole urban environment can be programmed and structured for change (Cook 72). The steel mega-structure contained major transport corridors and services. This structure supported a series of detachable living and working units that could be manoeuvred by cranes. The units responded to a hierarchy of obsolescence where those parts of the building that would need to be serviced and replaced more frequently, were most accessible. For example, the living modules and shopping areas, that had a three to eight year rating, were nearer the top of the structure, and heavy elements such as railways and roads, with twenty-year expectancy were nearer the bottom. (Cook 72)

Archigram's design schema of the Walking City was the ultimate step in disassembly and light urbanism, in which a forty-story building could literally disconnect from the site and move to a new location (Figure. 3.04).

The key to the work of Metabolists groups in Japan was a philosophy that allows for the replacement and change of components in such a way that the remainder of the structure is not disturbed. Such design concepts for disassembly were evident in their early works, such as Move – a housing system that used a housing module support system with a life expectancy of twenty-five years, attached to a mega structure support system. The 1970 World Exposition in Japan allowed Metabolist disassembly technology to be tested.

The capsule house in the Theme Pavilion of Expo 1970 was a cluster of individual pods that could be disassembled from each other, and from the mega-structure, so that individual changes in the use of the house could be accommodated (Figure 3.03). This concept was partially realised in Kurokawa's Capsule Tower in Tokyo 1972.

Archigram's ideas about the one-off dwelling were also thought provoking. Inspired by NASA's space suits and survival capsules, Mike Webb designed a pneumatic home, worn like a suit and inflated when required. Inflatable architecture appeared instant, flexible and organic. It could create pneumatic living environments carried in a suitcase that could be connected to other spaces for group leaving and entertainment. In the mid 1970's Future Systems pursued Archigram's ideas about mobility and adaptability on a smaller scale, by designing a minimal mobile house that utilises vehicle imagery and technology and could be located anywhere (Figure 3.06). The closest realisation of the concept of mobile, technological

Figure 3.05: ski-house, designed by Richard Horden (Horden 1995)

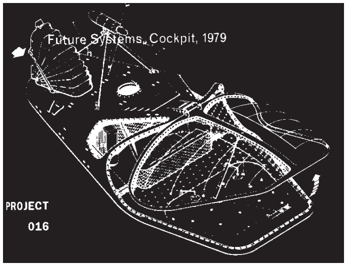


Figure 3.06: Mobile house, concept by Future Systems

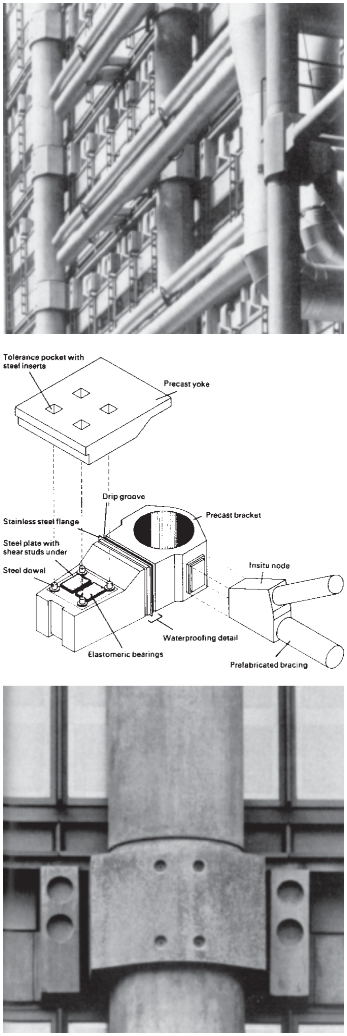


Figure 3.07: Lloyd's in London, Architect Richard Rogers

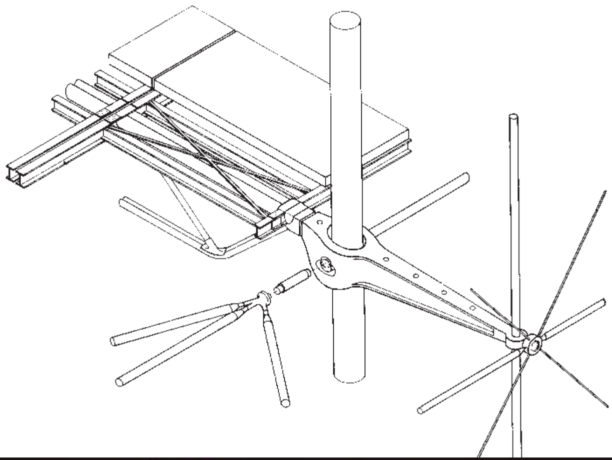
dwelling that can be dropped into any environment has been by Richard Horden with his ski-house for two people (Figure 3.05).

As previously mentioned, in addition to Archigram the work of Cedric Price is still seen as the greatest inspiration for the avant-garde movement of the 1960's and 1970's. His work concerns the application of different industrial technologies to achieve adaptability and greater building efficiency.

While the Interaction Centre, built in London's Kentish Town in 1971 put some of these ideas into practice on a reduced scale, Renzo Piano and Richard Rogers's Pompidou Centre would have been inconceivable without the Fun Palace.

Price's vision of constructing a dominant structural frame, against which a number of interchangeable building components could be placed from services, enclosures, and different partitioning units, can be clearly seen in the design of the George Pompidou Centre, Paris (Figure 3.08). This project enlarged the design vocabulary by treating all components equally, and by using services as decorative elements. The structural frame is more than 168 m long, and maps out the space. Vertical service elements are placed on the east façade. The glazing façade is placed behind the structural frame. Actually, services, circulation routes, and cladding materials have a secondary influence on the building's final appearance. The structural frame provides the organisation, controls the relief, scale, and visual detail, and in the end empowers the whole design (Andrew Orton 91). The building was declared by its designers to be a 'non-building' or a neutral framework in which various activities can take place, creating a form of architecture based on the events themselves. The building is an icon in the history of architecture, plays courageously with functions and their corresponding elements, and exposes them to the observer's eye. This celebration of building tectonics tells the story about how buildings work, from their functional and structural organisation, to their smallest detail. The structure literally decomposes itself in front of our eyes. Its frame contains the whole vocabulary of different types of elements and connections (from pinned to cast connections). It is this design of detail that gives refinement to the whole building, and accentuates the designer's determination to nurture change on all scales.

This concept is also found, in a more refined version, in Roger's project of Lloyd's Bank in London, and in Foster's Shanghai Bank in Hong Kong (Figure 3.07 - 3.09).



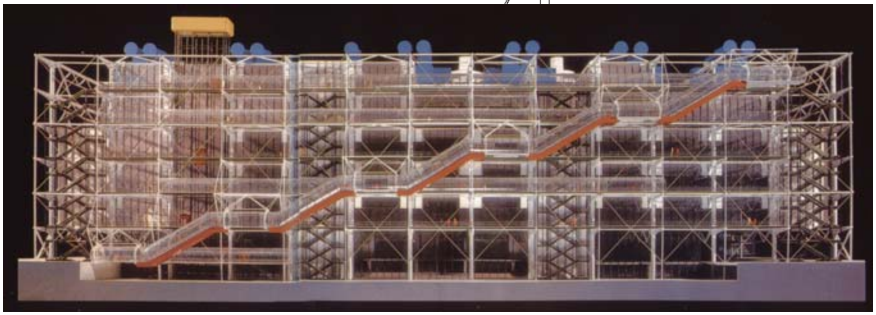


Figure 3.08 Centre Pompidou architects Richard Rogers and Renzo Piano

These projects make a clear distinction between the different functional groups of the building. They bring a focus back to the assembly and combination of functions and their materials at connections.

After observation of flexible buildings in the past, it can be concluded that their main characteristic is the development of new building techniques that improve structural and material performance and offered variety of products to answer different requirements. These techniques alter many building functions from being fixed to having less dependent conditions.

Consequently, independent building systems were developed as a performance driven systems where in use of materials and their arrangement into components and systems (by means of industrialised processes) was optimised to answer specific requirements. This resulted often into more efficient use of materials, better quality of components and buildings and greater client's satisfaction.

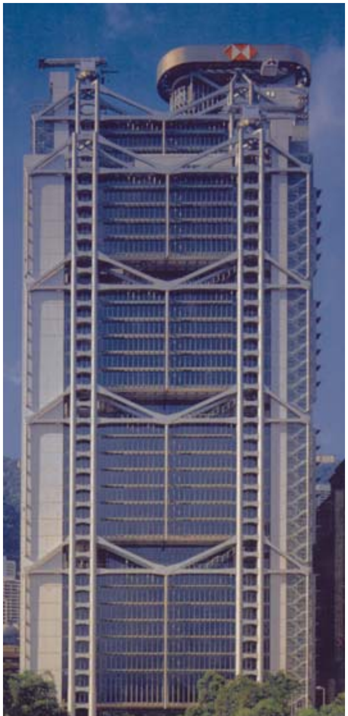


Figure 3.09: Bank in HongKong, Architect Norman Foster


Dutch Expo pavilion, designed by MVRDW

3.3 REDISCOVERING THE NEED FOR FLEXIBILITY THROUGH INTEGRATED LIFE CYCLE DESIGN

Although flexibility has often been at the centre of architects' debates in the past, it has never been widely accepted as a building concept. One can think of two reasons for this: one, related to the informal architectural language quite different from conventional ones, and other because of the fact that investors were usually confronted with higher construction costs compared with conventional building methods, since techniques that are more sophisticated were needed. By investing in transformable structures, clients invest in adaptability since these buildings in the future can do more things. Such buildings reduce development, maintenance, and demolition costs, and thus reduce total life cycle costs. A project that illustrates these benefits of flexible and demountable buildings is a new laboratory of hospital in Leiden (LUMC) (see Chapter 2).

Taking into account that:
- most modern building structures today use pre-manufactured elements designed to be mountable but not demountable end up in demolition processes whereby the building is broken up with little or no attempt to recover any of the constituent parts for reuse,
- demolition processes directly account for 90% of waste production within the building sector, approximately 50% of the embodied energy, and 40% of materials extraction, and
- more than half of the investment in construction is related to renovations and that about one quarter of new buildings replace demolished buildings whose materials and embodied energy are wasted.

One can say that at the turn of the 20th century, flexible and demountable building has provided another perspective. It is not seen as the aim in itself, but as a means to achieve the aim.
This new perspective is mainly a result of the fact that:

- Landfill costs and energy prices are drastically increasing,
- resources are rapidly diminishing,
- the demand for resources is growing, and
- development, maintenance, and demolition costs are increasing, as are total life cycle costs.

Results of many research studies, regarding sustainable construction, are summarised in reports by CIB deconstruction TG 39 group (Chini 2003) and the US governmental Green Building program (EPA 2005). These indicate that designing flexible buildings with exchangeable and reconfigurable/reusable components (Diagram 3.1), seen from the perspective of 21st century requirements, results in the reduction of construction and demolition (C&D) debris, conservation of landfill space, reduction of the environmental impact of producing new materials, creation of jobs, and reduction of overall building project expenses through avoided purchase/disposal costs. Furthermore, flexible buildings are easier to adapt to new requirements.

In short, such an approach to building design has the potential to accomplish benefits such as:

Environmental benefits
- Improvement of air and water quality
- Reduction in waste streams
- Conservation and restoration of natural resources
- Enhancement and protection oft biodiversity and ecosystems

Economic benefits
- Reduction in operating costs
- Creation, expansion, and shaping of markets for green product and services
- Improvement in occupant productivity
- Optimisation of life-cycle economic performance

Social benefits
- Enhancement of occupant comfort and health
- Heightening of aesthetic qualities
- Minimizing the strain on local infrastructure
- Improvement of overall quality of life

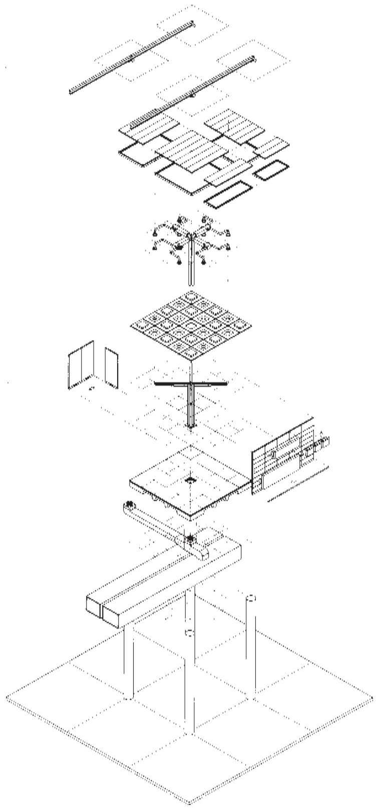


Diagram 3.1: Systematisation and integration of building elements into a buildig structure (Addis 1994)

Contrary to such structures, the existing built environment deals with fixed building structures whose end-of life is associated with demolition processes.
However, although there are many attempts worldwide to deconstruct existing buildings in order to benefit from reused components, examples show that such attempts are time consuming and labour intensive, making their economic feasibility questionable. The major barrier in accomplishing above listed benefits

is in a fact that disassembly aspects are not integrated into design plans. The fact is that these benefits cannot be accomplished without a fundamentally different understanding of the performance of the building and its parts, at the end of their use life. This includes consideration of different use strategies and end of life options for building and its materials from the beginning of the design process.

The key question is how to develop a design strategy able to replace existing fixed structures that are not designed for disassembly, adaptability, and material recovery, with open/dynamic structures that can be reconfigured and whose parts can be easily disassembled. Considering this to be the answer to such an approach should be looked in the transformation process itself because the transformation of buildings, systems, and components has to embody martial recovery options. In other words, the aim of sustainable design should be a design of transformable building structures made of components assembled in a systematic order suitable for maintenance and replaceability of single parts.

This concept affects design of all material levels that are accounted for technical composition of buildings and accentuates interdependent relation between transformation process and disassembly technologies.

Considering this, one can say that this concept introduces three dimensions of transformation in the buildings namely spatial, structural and material transformation.

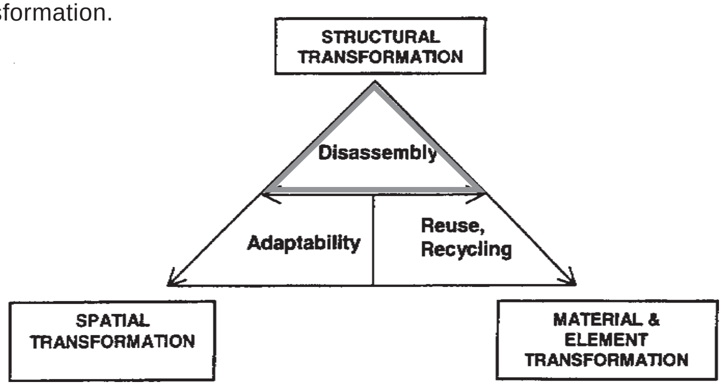


Figure 3.10: Three dimensions of building transformation, that have one criteria in common - disassembly

- Spatial transformation ensures continuity in the exploitation of the space through spatial adaptability,
- structural transformation provides continuity in the oprtation of a building and its components through replaceability, reuse and recover of building components, and

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

The key to each dimension of transformation and ultimately towards a three-dimensional transformable building, is disassembly (Figure10). By adoption of the concept of design for disassembly, spatial systems of a building become more amenable to modifications and change of use.
New steps in exploitation of structure by reuse and reconfiguration can be achieved, and conscious handling of raw materials through their reuse and recycling is stimulated. Thus, rather than destroying structures and systems while adapting building to fit into new requirements, it should be possible to disassemble sections back into components and to reassemble them in new combinations. When the act of demolition is replaced with disassembly, building components get a chance to have multiple lives, which can drastically extend their life cycle. Relation between disassembly and sustainable building is shown in Diagram 3.2.

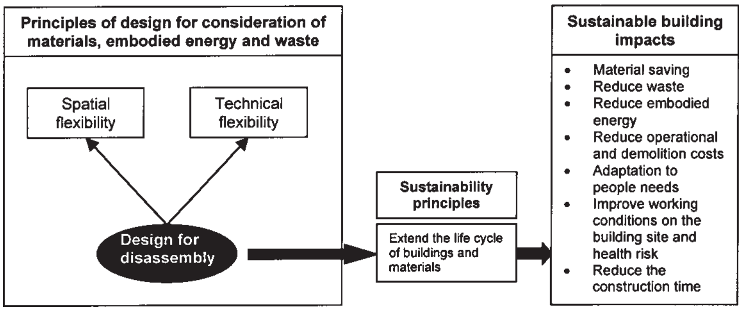


Diagram 3.2: Relation between disassembly and sustainable building

This 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.
The diagram 3.2 shows the positive impact that a DfD strategy would have on sustainable building. Comparison of the list of impacts with the list of sustainability demands per life cycle phase (table 3.0) indicates that a disassembly strategy has an impact on each phase of the building life cycle and can account for chnages in material, energy use and waste production.

Life cycle phase	Strategy per L.C. phase	Relevance
Design	• Development of scenarios for building use • Optimization of the building in each of its life cycle phases • Concurrent engineering	Flexible building Environmental burdens Timely and correct decision making Construction time
Manufacturing	• Use of material saving process • Use of recyclable or reusable materials • Use of low weight materials • Use of less energy intensive materials	Resource depletion Energy use Environmental burdens Resource depletion
Transport	• Low weight / volume	Environmental burdens
Assembly	• Dry assembly • Parallel assembly	Construction process Resource depletion Environmental burdens
Exploitation	• Low energy use • Design for maintenance/long life	Resource depletion Environmental burdens Resource depletion
Demolition	• Design for disassembly	Resource depletion Environmental burdens

Table 3.0: Sustainable strategy

In order to benefit from disassembly DfD strategy should be integrated into each life cycle phase of a building from the design to disassembly phase. Table 3.0 indicates DfD strategies.

Taking into account the potential that buildings designed for disassembly have, one may say that design of sustainable building runs the danger of being carried out on an ad hoc basis, without disintegration aspects of the building structure being an integral part of the design process.

Ultimately, the sustainability of design in the future relies greatly on the disassembly potential of building assemblies that determine the transformation capacity of building structures.

3.4 DESIGN FOR DISASSEMBLY AS THE KEY COMPONENT OF SUSTAINABLE DESIGN

The assumption in this research is that the level of buildings transformation capacity that relies on the disassembly potential of the building has a direct relation with the level of a building's sustainability. Higher transformation capacity means lower negative environmental impact and therefore higher sustainability (see Diagram 3.3).

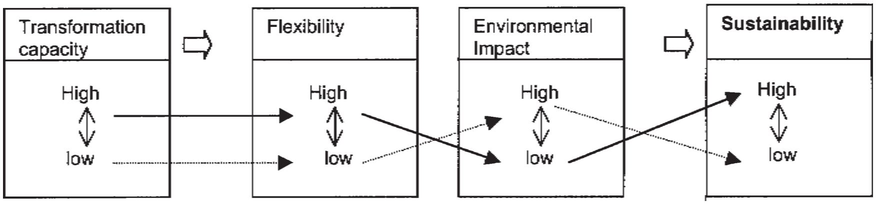


Diagram 3.3: High Transformation capacity = High Sustainability

Accordingly, buildings can be divided into three groups:

1. Building structures with low disassembly potential. Those are structures with standard construction waste stream (70-100% down-cycling and demolition).
2. Building structures with partial disassembly potential (30-70% of materials are down-cycled land filed or incinerated).
3. Building structures with high disassembly potential (0-30% of materials are down-cycled, land filled or incinerated).

Increase of the disassembly potential of buildings through the optimisation of design aspects for disassembly can drastically improve the environmental and use efficiency of buildings. (Diagram 3.4)

	Transformation capacity	Scenarios for material use
1	Transformation capacity of structure is low	Scenario 1 standard waste streams in construction
2	Transformation capacity of structure is partial	Scenario 2 reuse of most of the components 50%
3	Transformation capacity of structure is high	Scenario 3 high level of reuse 80%

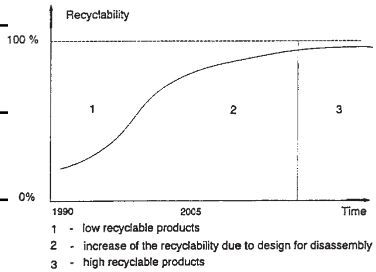


Diagram 3.4: Relation between transformation capacity and demolition waste

If design for disassembly was adopted as a common design practice, it would allow existing and new building stock to serve as a primary material source for new construction, rather than harvesting resources from the natural environment.

In order to move towards such scenarios we need to change our perception of the building's technical composition, from being permanent and fixed, to being changeable and open. The main discussion in this dissertation is related to the principles of design for disassembly, in order to propose a guideline for design for disassembly as a form of environmentally responsible architecture.

3.4.1 WHEN DOES DISASSEMBLY TAKES PLACE

The key issue in developing a new design strategy that integrates disassembly aspects of building configurations, is to understand how buildings behave through all phases of their life cycle, and under which agents they change. The dominant aspect of buildings is that they are collections of materials and systems brought together to serve particular functions. For that reason, each material or system is associated with two life cycle types: one related to the durability of the material or moment of structural failure, and another related to the durability of the functions that materials are to fulfil. In other words, we can talk about technical and use life of each material, component, and system within the building.

Conventional building structures usually follow the pattern of fixed integration of technical components into closed systems. Consequently, these systems are integrated into fixed spatial systems in the building. Taking into account such a general dependency from material systems to spatial systems, every change within a building can result in demolition of parts of the building. One factor that encourages this is building components that cannot be extracted from the structure. Such a static approach to integration ignores the fact that building components and systems have different use and technical life spans. 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. Because of this, buildings tear themselves apart. To avoid

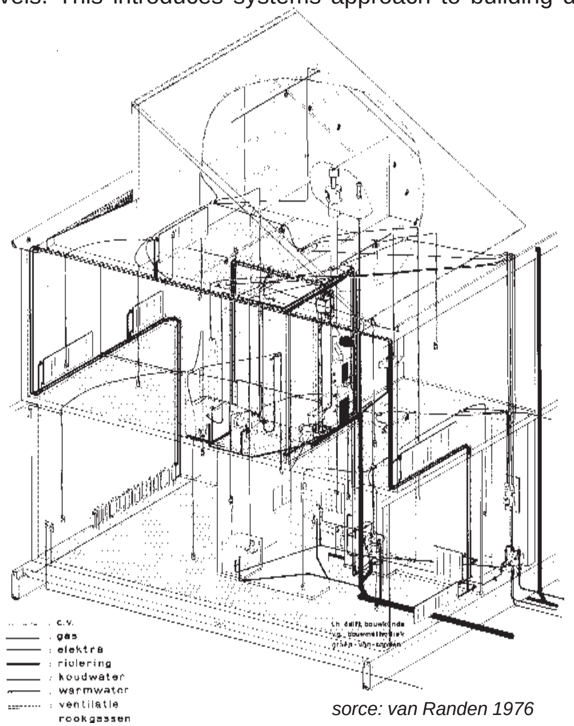
** The slow time levels represent the elements with:*
- *high durability (60-100 years or more) and*
- *high level of flexibility towards spatial and functional changes.*

The fast time levels represent the elements:
- *with short life cycle (5-60 years)*
- *and elements which are exposed to the change due to the change of the requirements (related to the new user or to the new technical requirement)*

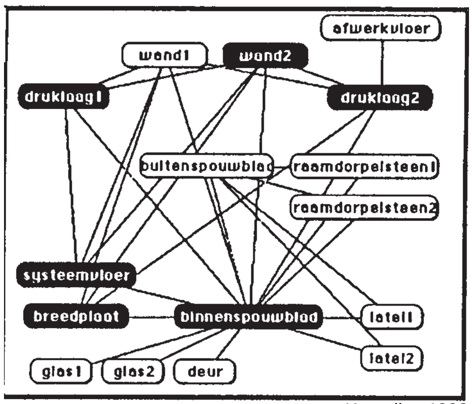
such an effect, components whose changing rates are different, should form independent time layers. The first step towards managing the temporal tension in building is through decoupling of slow and fast time levels (Kibert 2000).

The question is how do we recognise changing layers, when one building represents a system of planes, lines, and points broken into a number of material levels, which again interact with each other on different physical levels that form ultimately technical composition of the building structure? This effect is similar to the ‘spaghetti effect’ in building, a term that was first used in building construction by Van Randen in 1988.(Diagram 3.5)
In order to resolve this effect so that building parts can be decomposed during exploitation of the building and at the end of their design life, a more systematic approach to building design is needed. The methodology, which is used in this research to define the building in more systematic way, is one that relies on theory of levels. This introduces systems approach to building design.

Diagram 3.5: Relational diagram shows dependencies between building components within one housing project.



sorce: van Randen 1976



sorce: Kapteijns 1992

3.5 THEORY OF LEVELS

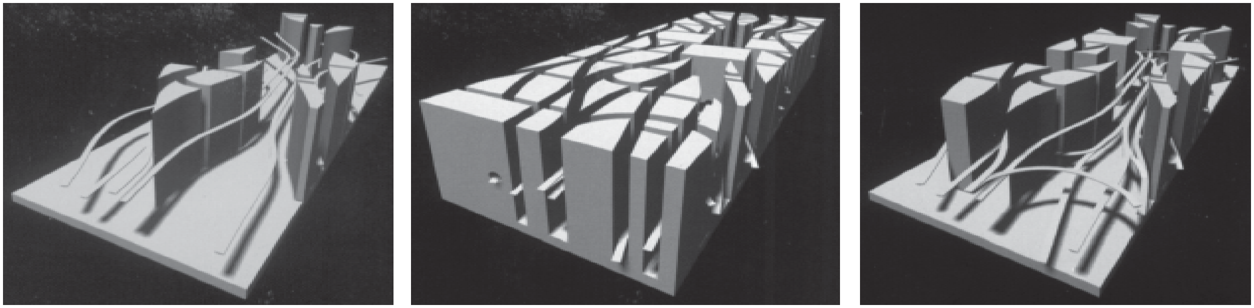
Obviously, buildings are complex entities. In order to understand and evaluate their performance, a method has to be defined that will help to systematise their parts into understandable and controllable clusters. Most researchers that dealt with this complexity used to define a building through the different types of levels in order to achieve this. Levels are usually defined according to the changing sequences of studied aspects. The theory of levels introduces systematisation of studied aspects into number of independent levels. It defines their hierarchy and accordingly dependence between the fast changing and slow changing levels.
Regardless of the type of levels, studies that look at the building through a theory of levels, prove that building is incorrectly referred to in the singular. This is result of the misconception resulting from looking at the building in limited time frames. The basic argument that was brought by Duffy in his book 'Measuring Building Performance' is that there is not such a thing as a 'building', a building properly conceived is several layers of longevity of built components.
Thus, building is a multidimensional system that can be represented through different types of levels. In order to identify independent responsibilities of parties involved in transformation of built environment Habraken introduced levels of control/decision making, while Duffy and Brand defined functional levels within a building in order to identify functions with different changing rates in a building. This research introduces an additional view on building structures through levels of technical composition that represent integration of functional and material building levels. Analysis of buildings through levels of technical composition help us to identify building materials that have different functional/use and technical life cycles, and more importantly to identify materials that have embedded disproportion between functional and technical life cycle what makes them even more disassembly sensitive than the others.

A major assumption in the theory of levels is that some levels dominate others. This dominance is defined by their changing rates. The dynamics of the systems is dominated by the slow components with the rapid components simply following along (O'Neill 86). The levels that have longer durability (the slow cycling levels) dominate the levels that have shorter durability (the fast cycling levels). When putting this back into the context of design of transformable structures and their technical composition, one can say that the ultimate task of design for disassembly is to reduce interrelated dominance between functional and physical levels within a building structure, because fast changing functional levels will provoke demolition of slower changing physical levels. On the other hand, fast changing physical levels will affect integrity of slower changing functional levels. This may result in demolition of some building parts as well. In order to avoid this dependence, slow levels should set limits rather than be didactic, such that structures can become more preventive and open-ended rather than curative.

3.5.1 Levels of control

The question of the building decomposition and independence of building levels has been addressed in different ways, many times in the past. A well-known approach is the one that addresses the independence and decoupling of the levels of decision making within the built environment. This theory points out that organising planning through a system of hierarchical progression of independent levels of decision-making provides a great deal of flexibility and freedom in adjusting to changing economic, demographic, and technological circumstances. This approach was first recognised in the work of Professor Habraken who introduced the theory of levels of change in 1960's in his book 'De Dragers en de mensen' 'Supports. Habraken suggested that the built environment could be divided into three levels of decision making, namely: urban fabric or tissue, base building or support, and fit out or infill. This hierarchy of levels was developed following the pattern of responsibilities or control. The building interacts with inhibitants at the infill level (inhibitants define the infill level), the tenant organisation is responsible for the support level, and the whole community is responsible for the tissue levels. The community accomplishes this through decisions about the footprint and the volume of the support, and about connections on the main infrastructure of the city

Figure 3.11: Fixed and flexible elements of urban fabric



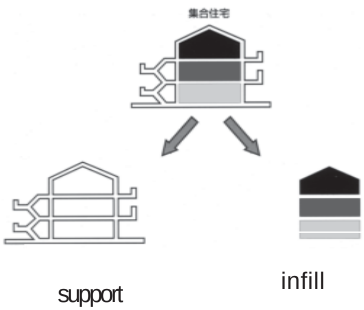


Figure 3.12: fixed and flexible elements on building level (Kamo 2000)

and restrictions on the site. The town fabric (urban tissue) is at a higher level than a building positioned within an urban fabric. Buildings can be transformed and demolished, while the urban fabric stays the same. In other words, urban fabric is the stable backdrop against which buildings transform (Habraken 1998). (Figure 3.11)

Within the building block, the distinction was made between support and infill level. Habraken understood the support as the 'spring board' accommodating change of use. It provides potential to the infill, to be assembled, altered, and taken down independently of one another. The support structure can be seen as building 'land in the air', which holds communal facilities, as well as connections for installation services (Figure 3.12 and 3.14). (Franke 2003)

Habraken argued that we can observe these levels operating in the way the built environmnet transforms.
A support remains constant during interior renovation . Lower level (infill level) configurations transform more easily and therefore with greater frequency than higher (suport) level configuration (Habraken 1998).
Figure 3.13 left shows a vertical dependent hierarchy of levels of decision-making within one housing block, where changes in one level automatically provoke changes on another. This means that all levels have 'the same age' and are treated at the 'same time' to the 'same extent'. In contrast to such a fixed condition, Figure 3.13 right shows independent horizontal levels of decision making that provide a flexible framework for future modifications of lower levels (as for example infill level).

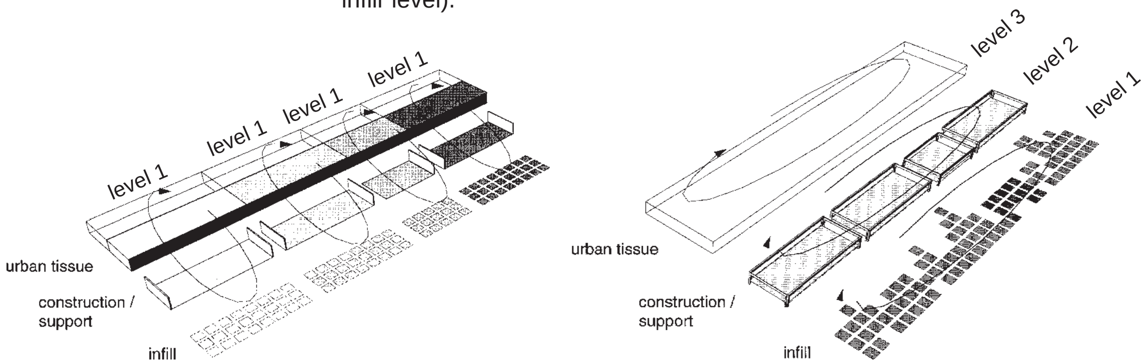


Figure 3.13: left: fixed structure dependence between three levels of decision making), right: transformable structure (three independent levels of decision making) (Cuperus, Kapteijns 1991)

Such an open process recognises different life cycles for infill and support level This broadens the building's capacity to adapt to user's future requirements.

Leupen used Habraken's definition of support and infill to illustrate possible variations that could be achieved in architectural language. The name support is not derived from its definition as a physical load bearing construction, but from the fact that it has to provide for what the occupants, as a community, share. Elements forming the façade might be part of the support in one case and part of the infill in another. The same is true for the services and partitioning walls. Leupen has added two more levels: installations, and 'stuff'. He suggested that flexibility and variation is derived primarily through combination of five functional levels of the building site, support, infill, installations, and stuff on two levels of decision-making support and infill (see Figure 3.15).

Figure 3.15 left presents a solution where the load bearing structure and façade are part of a 'support', Figure 3.15 Middle: installations and separation wall as support and Figure 3.15 right: load bearing structure as 'support'. By making such analysis Leupen argued that the combinations within the support and infill levels of control have an impact on the variation of architectural design.

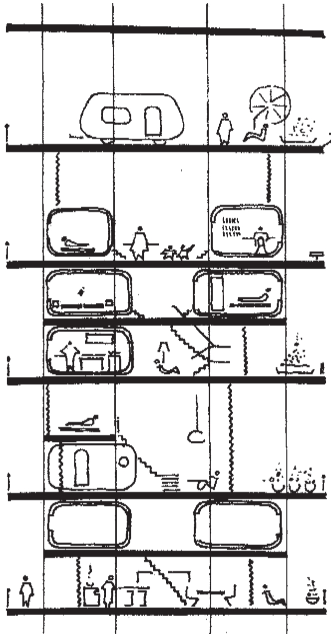
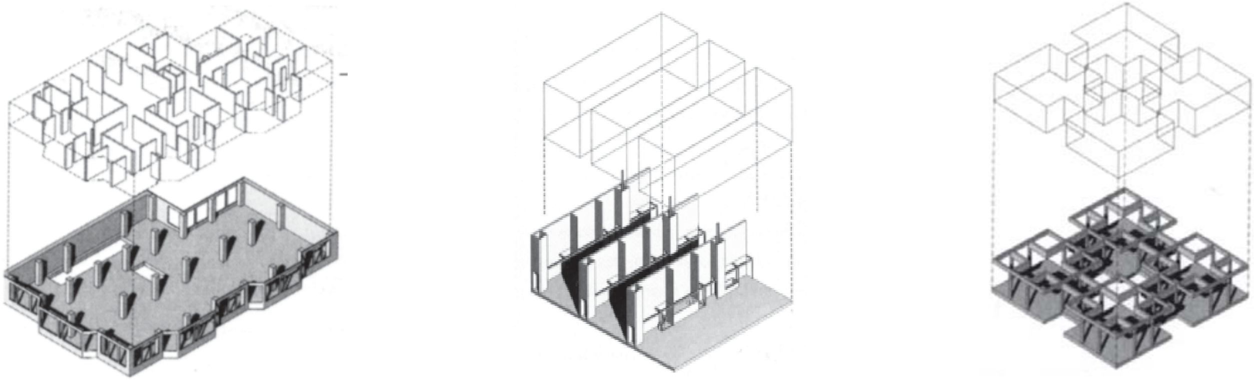
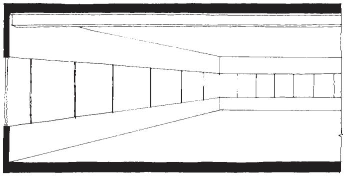


Figure 3.14: Habraken support and infill 1963 (Bosma at all 2001)

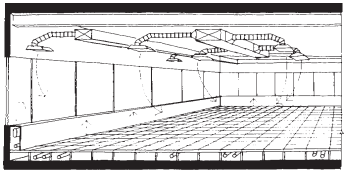
Figure 3.15: Type of flexibility determined by the combination of fixed and flexible levels (Leupen 2002)



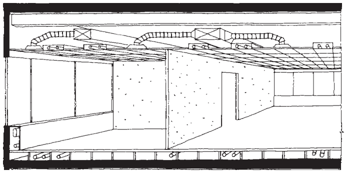
Shell: 50 to 75 years



Sevices: 10 to 15 years



Scenery, fitting out elements: 5 to 7 years



Settings, office furnishings: day to day

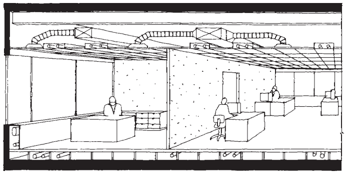


Figure 3.16: Building layers according to Duffy(Duffy 1998)

3.5.2 Functional time levels

Another approach to systematisation of changing levels within the building is provided by a group of researchers Duffy and Brand who argue that systematisation of building should be followed by the use life cycle of different building components. While analysing the nature of change in office buildings, Duffy defined building through four layers the so-called four S's: Shell, Services, Scenery, and Set.(Figure 3.16).

* Shell is the main structure of the building and has a life span as a building on average of 50-75 years (in USA and Japan: 30-35 years).
* Services are installed such as cabling, plumbing, air conditioning, and vertical communications (lifts). Their design life is 15-20 years.
* Scenery is the layout of partitions, dropped ceilings, and finishes that change every 5-7 years.
* Set is the furniture that is placed and moved by the occupants within weeks or months.

Another well-known systematisation of layers is Brand's model, which expands upon Duffy's four S's (Shell, Services, Scenery, and Set).

Brands model consists of site, structure, skin, services, space plan, and stuff (Figure 3.17).
* Site: the urban location; the legally defined lot whose context lives longer than buildings. According to Brand and Duffy, the site is eternal.
* Structure: the foundation and load-bearing elements, which last between 30-300 years. However, few buildings last longer than 50 years.

* Skin: the exterior finishing including roofs and façades. These are upgraded or changed approximately every 20 years.
* Services: the HVAC (heating, ventilating, and air conditioning), communication, and electrical wiring. They wear out after 7-15 years.
* Space plan: the interior layout including vertical partitions, doors, ceiling, and floors. According to Brand, commercial space can change every 3 years.
* Stuff: the furniture that is moved daily, weekly or monthly. Furniture, in Italian is called mobilia, in Dutch meubel, in German moebel, for good reason.

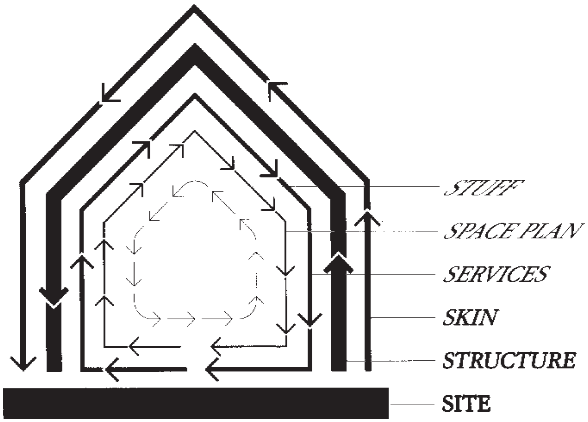


Figure 3.17: Building layers according to Brand – sharing layers of change(Brand 1995)

The questions that arise from the perception of the building as a combination of functions and materials with different changing rates, has opened discussions regarding building serviceability. In some countries, these discussions have resulted in new building code concepts.

For example, in 1992, a new building code was published in New Zealand that contains quantitative requirements for the service life of various parts of buildings, and for construction products.

In the clause B2 Durability, requirements are given in the following way:

“B.2.3 From the time a code compliance certificate is issued, building elements shall with only normal maintenance continue to satisfy the performance of this code for the lesser of; the specified intended life of the building, if any, or:

(a) For the structure, including building elements such as floors and walls which provide structural stability, the life of the building being not less than 50 years.

(b) For services to which access is difficult, and for hidden fixings of the external envelope and attached structures of a building: the life of the building being not less than 50 years.

(c) For other fixings of the building envelope and attached structures, the building envelope, lining supports and other building elements having moderate ease of access but which are difficult to replace 15 years.(NTNU Department of Building and Construction Engineering March 2001).

In a Guidance Paper published by the EU in 1999, a table of assumed working lives of works and construction products is given Table 3.1 and 3.2). The table was developed by the European Organization for Technical Approvals (EOTA) and is another example of how quantitative values are given for service life, in which architects, consultants, authorities, and manufacturers of building products have to take into consideration and be able to fulfil.

Table 3.1: Categories of design service life for buildings. (From /16/)

Category	Design service life for building	Examples
Temporary	Up to 10 years	• non-permanent construction buildings, sales offices, bunkhouses • temporary exhibition buildings
Short life	10 to 24 years	• temporary classrooms
Medium life	25 to 49 years	• most industrial buildings • most parking structures
Long life	50 to 99 years	• most residential, commercial, and office buildings • health and educational buildings • parking structures below buildings designed for long life category
Permanent	Minimum period 100 years	• monumental buildings (eg. national museums, art galleries, archives) • heritage buildings

Table 3.2: Assumed working lives of works and construction products

Assumed working life of works (years)		Assumed working life of construction products (years)		
Category	Years	Category		
		Repairable or easily replace-able	Less easily repairable or replaceable	Lifetime of works **
Short	10	10 *	10	10
Medium	25	10 *	25	25
Normal	50	10 *	25	50
Long	100	10 *	25	100

Functional levels discussed by Duffy, Brand, and Leupen are multidimensional and do not have consistent life cycles. This can be illustrated with installations that are mentioned as one functional level. However, there are six major installation services: electrical supply, water supply, sewage system, ventilation, air conditioning, and heating. They all have different functionality and changing rates. Thus, these constitute six additional functional levels. Furthermore, we can consider installation systems, city distribution networks, main building supplies, and space distribution networks. Thus, we arrive at nine new changing functional levels related to the installation system. Furthermore, each has a number of physical levels, depending on the design program. Each of these levels will have different use and technical life cycles. Therefore, the attempt to fix the number of changing levels is misleading as a concept for the design of transformable structures that rely on disassembly of changing physical levels and materials.

3.5.3 Beyond studied aspects - Levels of Technical Composition

Specification of buildings through functional levels addresses transformation from only one dimension and recognises that disassembly is needed because different components within a building have different use life cycles. However, there is another dimension — that of technical life cycles. While for example one façade has a functional/use life cycle of 20 years, while its component parts have different technical life cycles, which may vary between 10-100 years. The difference in use and technical life cycle of building components presented in Figure 3.18 indicates that different changing rates of functions on the building level should allow façades to be independent since their use life cycle is two times shorter than the use life cycle of the construction elements and two times longer than the use life cycle of partition elements. Furthermore, the arrangement of material levels within the façade system itself should recognise that each material has different durability and therefore should be seen as an independent part of the structure.

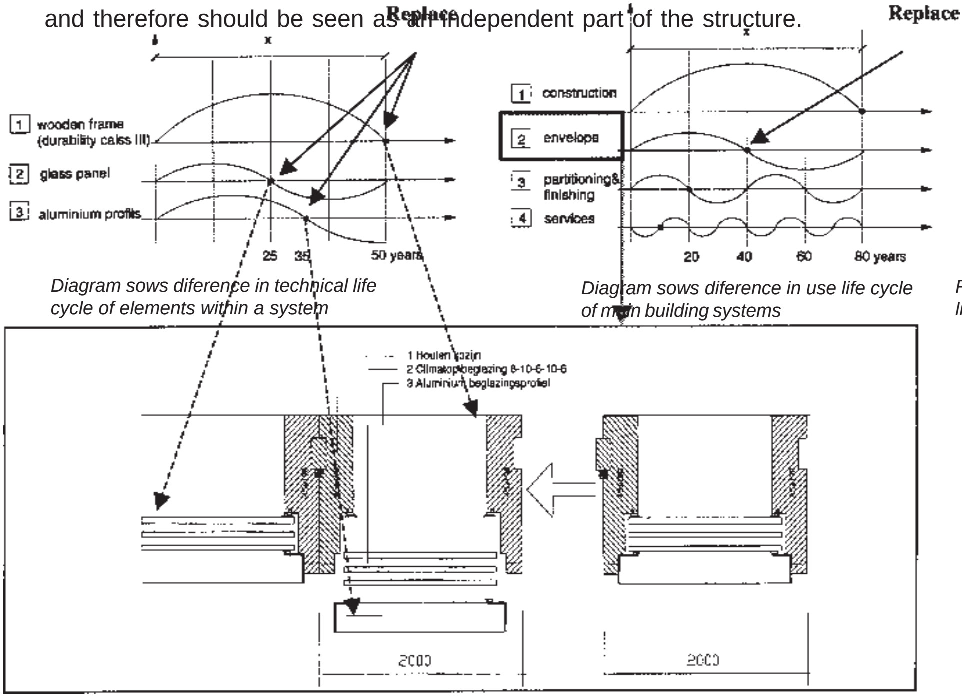


Diagram sows diference in technical life cycle of elements within a system

Diagram sows diference in use life cycle of main building systems

Figure 3.18: Different use and technical life cycle of façade system.

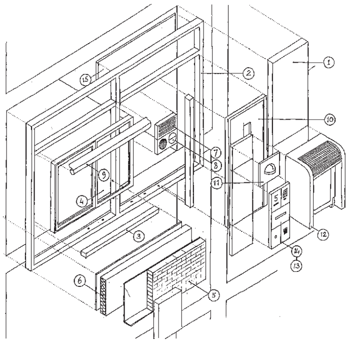


Figure 3.19: Technical composition of one façade(Kapteijns 1998)

Thus, transformation of buildings and independency of its parts does not rely only on functionality of an assembly and its use life cycle. In other words, Brand's shearing levels of change that tears buildings apart should be looked at beyond the use time levels of the building parts, since independence is also needed to separate components, which have different technical life cycle. Each physical level within a building deals first with its own life cycle duality, and secondly with the fact that surrounding components may have different changing rates. In order to be able to identify physical levels of building that have different use and technical life cycle one should focus on the technical composition of building structures as it integrates functional and material levels and therefore can incorporate use and technical life cycle coordination. Technical composition deals with systematisation of materials according to desired functionality and arrangement and integration of materials into specific physical level. How we call a specific physical level will depend of level of technical composition within the building. Major levels of technical composition can be called components, systems, and building and will have number of sublevels. (Figure 3.19) Higher level will dominate lower level of technical composition. Accordingly, use requirements for the system have embedded requirements for the development of system components. However, requirements for the system may change over the time or simply some components should be replaced for reasons of maintenance. This may require changes on the lower physical levels. Traditionally, durability of functional levels has determined the durability of physical levels. When independence and exchangeability of physical levels that have embodied disproportion between use and technical life cycle is adopted as a design strategy, the life cycle of physical levels and consequently materials can be extended.

This aspect of independence of building components can guarantee more efficient use of building materials that brings environmental benefits and can contribute to sustainable development. When considering this, buildings gain greater numbers of changing levels, since both the functional/use and physical/technical time levels are considered. The use life cycle depends on the change frequency of spatial systems. The technical life cycle depends on durability of materials and interfaces. The coordination of use and technical life cycle within physical levels and between physical levels is a major task of technical composition of transformable building and its technical systems.

Possible scenarios for systematisation of building along the levels of technical composition are presented. The examples show that emancipation of physical levels goes hand in hand with transformation requirements, and that greater transformation of building means greater number of independent physical levels.

3.6.4 Emancipation of physical levels

Typical housing in Holland 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. Figure 3.20 left shows integration of functions of a building into physical levels. These are arranged during technical composition into one fixed physical level whose use and technical life cycle was assumed to be 75 years. However, recently some housing corporations indicate that use life cycle of one layout typology is even shorter than 25 years, and that most building parts are demolished and wasted during transformation of a spatial system from one typology to another. It has been suggested that if a dwelling would have ability to accept some short use phases related to repartitioning of the space for example, then some life cycle of some physical levels such as partitioning elements and services could be extended. Figure 3.20 right shows emancipation of five physical levels that provide the opportunity to modify dwelling according to different use pattern.

This concept illustrates that the life cycle of five levels of technical composition of building is extended by their ability to accept shorter use phases (with respect to repartitioning of the apartment space).
The project that has provided an even greater number of independent physical levels for the purpose of greater adaptability is the Next 21 Project in Osaka (Figure 3.21). Flexibility of the façade, installations, and infill systems were a leading concept in this project. (Figure 3.22 a) The functional levels are defined by eleven independent physical levels (see Diagram 3.6). This has been a result of desired use requirements such as having total spatial and functional flexibility in the dwellings, being able to reposition windows, extend apartments, and to access all installations for their maintenance and upgrading.
This has resulted in the design of an external envelope made up of movable steel frames covered with aluminium strips.

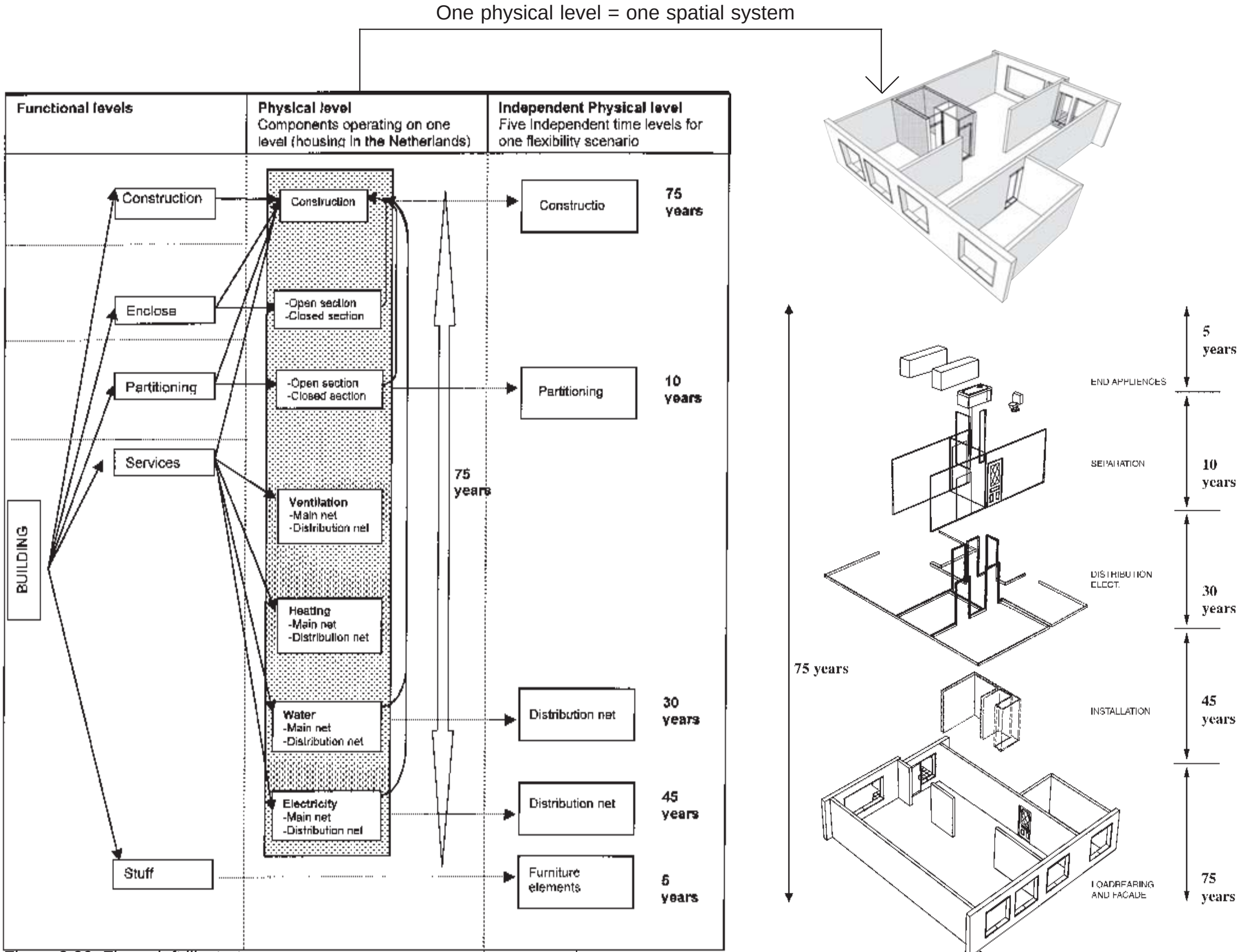


Figure 3.20: Figure left illustrates one housing project in Holland which freezes most of the functional levels in one fixed physical level, figure right shows an alternative solution where five physical levels have been separated. Five independent levels provide easy reconfiguration of building partitioning and electric components.

The façade system can be reconfigured by moving or adding window or door openings, as well as by integrating the balcony into the dwelling space, or by creating a new balcony (Figure 3.22 b). Short-life piping facilities are installed separately from the main structure and can easily be updated.
The space above the ceiling and in the floors of each dwelling is effectively utilised, while use of wastewater pumps makes it possible to position toilets, bathrooms, and kitchen, wherever needed. (Kendall 2000)
A highly flexible partitioning system has been put in place so that apartments can easily be remodelled by reusing existing components. The infill system allows a total reorganisation of the unit's layout.
The emancipation of these physical levels to allow these transformation scenarios of the building and its systems is shown in Diagram 3.6.

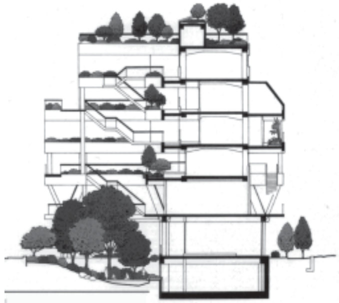


Figure 3.21: 3D structural frame for the Next 21 project in Osaka

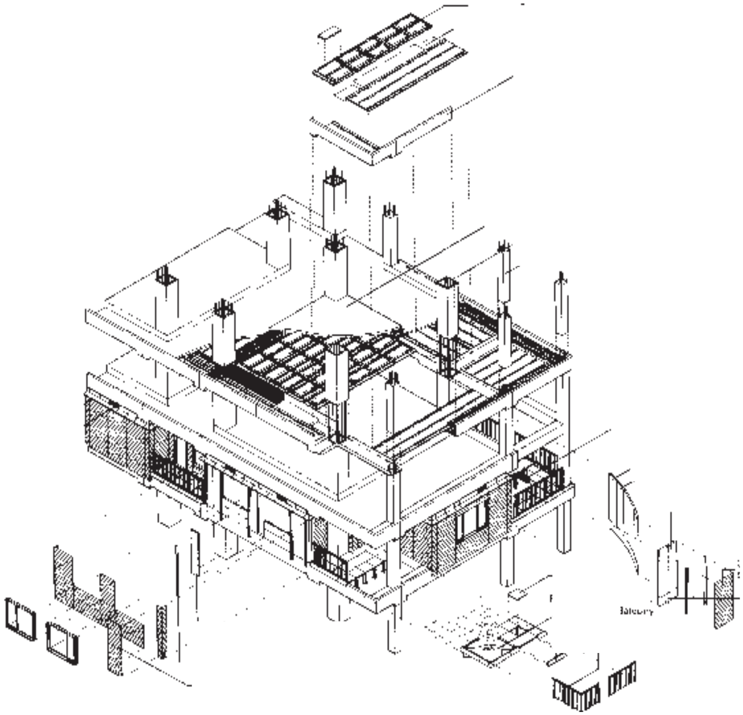


Figure 3.22 a: Separation of building components (Kamo 2000)

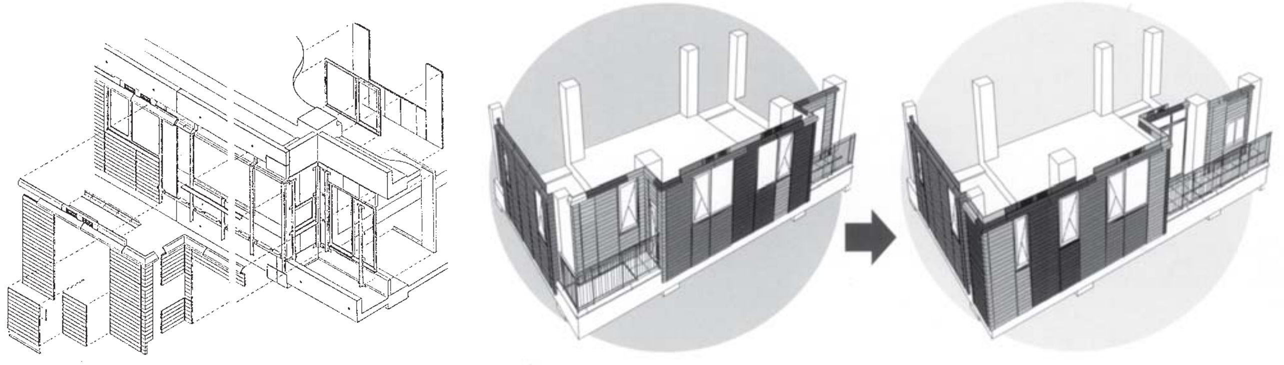


Figure 3.22 b:Transformation of the External envelope (Fukao 1999)

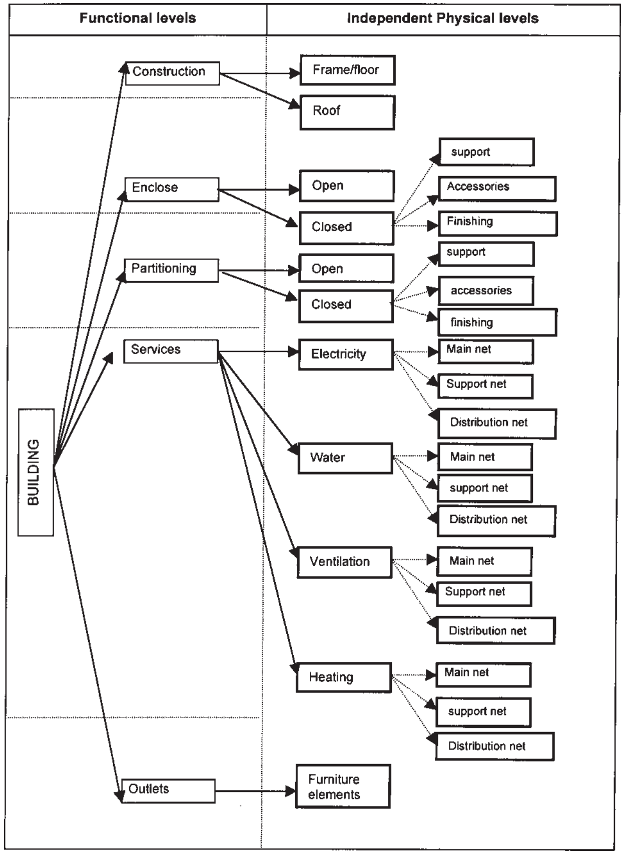


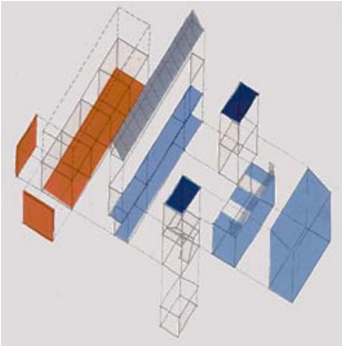
Diagram 3.6 illustrates the number of independent physical levels within the Next 21 project

3.6 THE KEY CHARACTERISTICS OF TRANSFORMABLE STRUCTURES

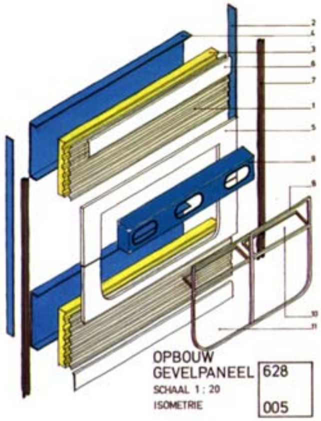
An important contribution of studies by Habraken, Brand, and Duffy is that they indicate that building is not a static entity. However, if we want to explore transformation further than a fixed number of changing levels, as suggested, becomes ambiguous. The number of changing levels is increased with 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 transformation capacity of building and recycling of materials, is the dominant issue in design for disassembly.

Performance requirements define the boundaries within which these levels are intended to operate. The concept of transformation and independent material levels is not restricted to one scale (Diagram below). The desired use scenario and its functional decomposition, durability of used materials, and the end-of-life scenario of the products (reuse, reconfiguration, down cycling, and up cycling) define the actual number of independent levels per building.
Each physical level can be further divided into sub-levels, which can be recursively composed of additional sub-levels (Figure 3,23). Their hierarchical dependence moves along this subdivision. One can say the greater desire for transformation on building, system, and component level, for the reason of their reconfiguration, reuse and recycling, results in a greater number of independent materials. Theoretically, this number can grow indefinitely (Diagram 3.07).

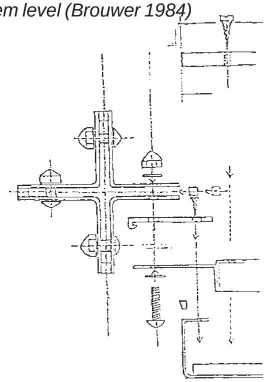
The focus of this research will be on Design for disassembly aspects of technical composition of building and its parts. Habraken wrote that transformation results from agent action; it highlights parts and configurations under agent control. That control in turn defines the units of transformation. In addition to that, the two agents that define the units of transformation of sustainable buildings are technical, and use durability of their components.



Building level (Brouwer 2001)



System level (Brouwer 1984)



Component level (Les Corbusier)

Figure 3.23: Example of the separation of all material/physical levels within the building (from systems to materials).

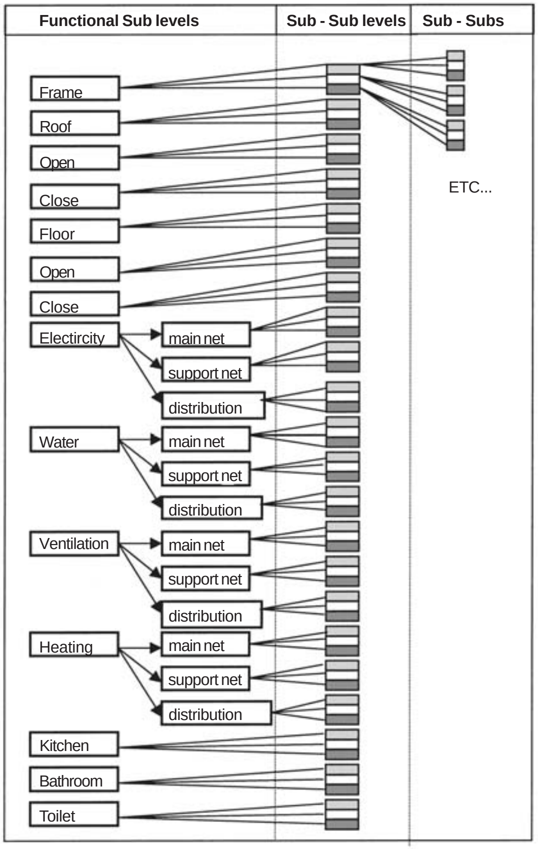


Diagram 3.7: x number of physical levels

This is manifested through identification of physical levels and its materials that embedded disproportion between use and technical life cycle.

The first step towards assessment of independent physical levels is through identification of physical levels and its materials that embedded disproportion between use and technical life cycle.

This can be represented using a life cycle coordination matrix presented in figure 3.24.

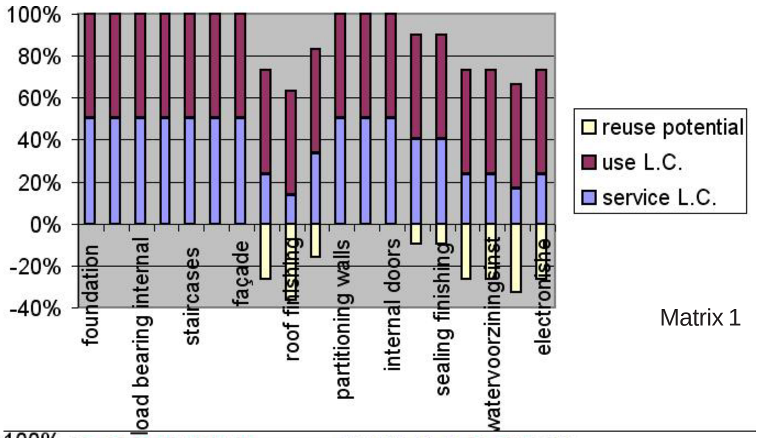
3.6.1 Life cycle coordination matrix

In order to highlight independent/disassembly sensitive materials two types of information are needed. First, information is required about what the use strategy of the building through its whole life cycle is. This will help provide estimation regarding the number of functional levels, and accordingly their use life cycle. Second, what are the proposed materials to be used in order to provide desired functionalities? This will help to make an estimate with respect to the number of material levels and technical life cycle of used materials. This research argues that if we put this information together we can create a life cycle coordination matrix that will indicate elements that embed a high disproportion between use and technical life cycle, and therefore high reuse potential. The argument here is that in general all elements within the life cycle coordination matrix that indicate disproportion between two life cycle types should be considered as disassembly sensitive and environmentally and economically valuable parts of the structure. Obviously, the discussion about how big the disproportion between use and technical life cycle can be will be raised. However, the answer will depend from the type of specific material that is to say, its market value, ecological footprint including embodied energy that can be saved through reuse. Establishment of this merge per type of material only, can be a subject of specifies research.

In figure 3.24, three life cycle coordination matrixes are illustrated. They represent three distinct types of building structures whose graphical representation can be seen in Figure 3.25.

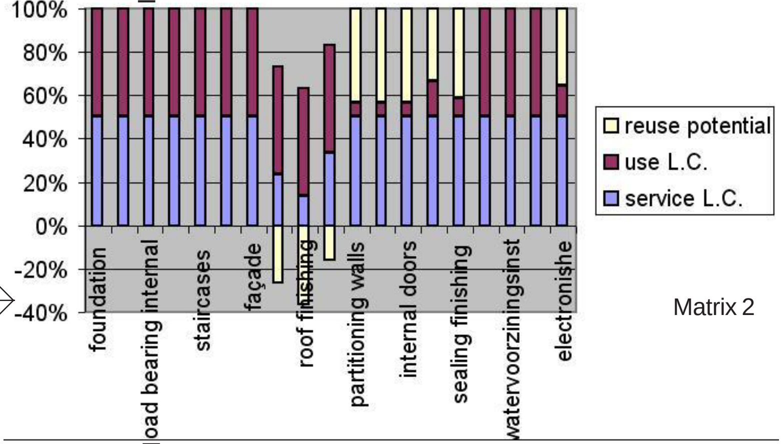
The first matrix (Figure 3.24) represents a typical housing project previously discussed in this chapter with conventionally used materials and use strategies. This housing was designed for a fixed spatial system. Such strategies resulted into fixt technical system/one physical level. The strategy of housing at the time was as that instead of adapting space to different life phases, users of dwellings can move as they would progress from one phase in life to another; houses were built for singles, couples, families, old people, disabled etc. This life cycle coordination matrix indicates that there are few maintenance sensitive components in this building since the use life cycle of for example façade windows or heating installations is longer than their technical life cycle.The second matrix (Figure 3.24) represents technical composition for housing based on use strategy estimations of housing corporations in Holland such as “Het Oosten”. The strategy recognises a need for adaptability along the different phases in life and requires

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

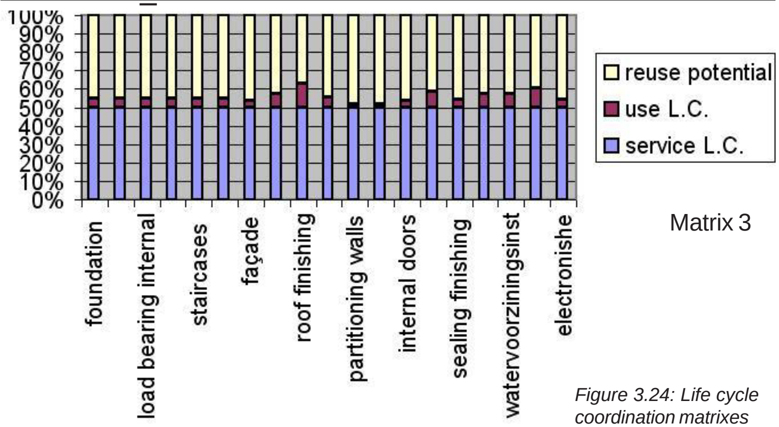


Matrix 1

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



Matrix 2



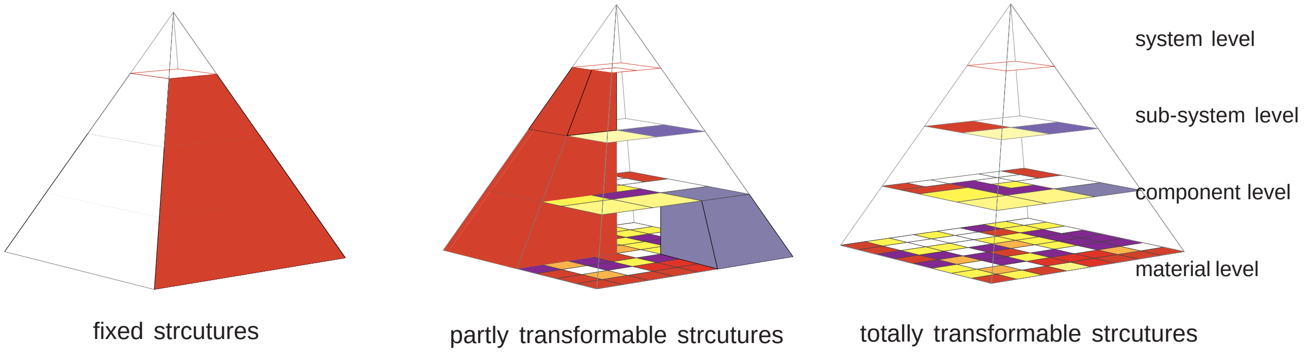
Matrix 3

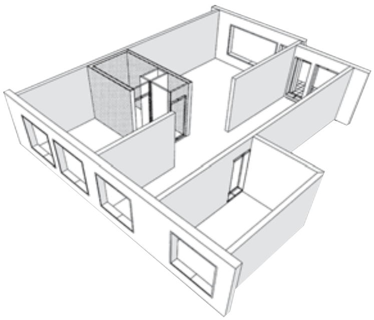
Figure 3.24: Life cycle coordination matrixes

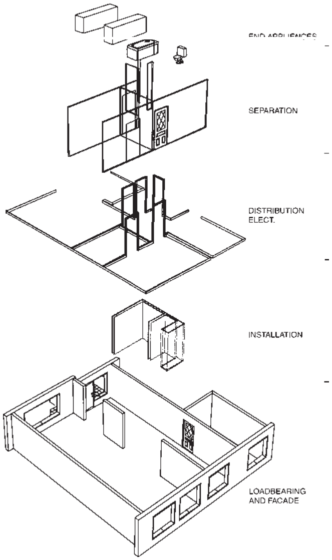
independent parts that could be replaced, reconfigured, and reused. Emergence of such concept was not the result of environmental awareness but of market conditions and demand. In this concept, distinction could be made between fixed and transformable physical levels of technical composition. This life cycle coordination matrix indicates that besides maintenance sensitive components in this building there are few components that have high reuse potential because use life cycle of partitioning walls and doors for example is much shorter then their technical life cycle. Those are at the same time disassembly sensitive elements and should be designed as independent physical levels and positioned higher in disassembly hierarchy.

Gradually increasing dynamics in the real estate market associated with growing number of short use sequences is moving hand in hand with environmental requirements demanding different approach to resource consumption. Such requirements are moving towards technical compositions that will represent completely transformable structures which are adaptable and whose elements are reusable and recyclable. This strategy is shown though lifecycle coordination in the third matrix (Figure 3.24). This matrix represents an extreme scenario, which requires total changes of spatial systems on average every 7 years. This life cycle coordination matrix indicates that all components that were used in this building have high reuse potential because use life cycle of all components is much shorter then their technical life cycle. In order to be able to recover materials during the transformation and demolition phase of the building, all physical levels of this building should be independent and dismountable.

It is evident that each use scenario imposes different use life cycle on building components. Add to the fact that building components have different durability, it can be concluded that every use scenario will have different numbers and hierarchies of physical levels, and therefore a different hierarchy of technical systems. The hierarchy and physical dependency between physical levels corresponds to a desired transformation strategy. Having this in mind, all building structures could be divided into three groups, such as fixed structures, partially decomposable structures, and totally decomposable structures. The process of transformation from massive to decomposable structures symbolises the process of separation of building functions, according to use strategy, from fixed to fewer dependent conditions. The dependences within technical systems and levels of technical composition are frequently the result of fixed physical interaction between them.







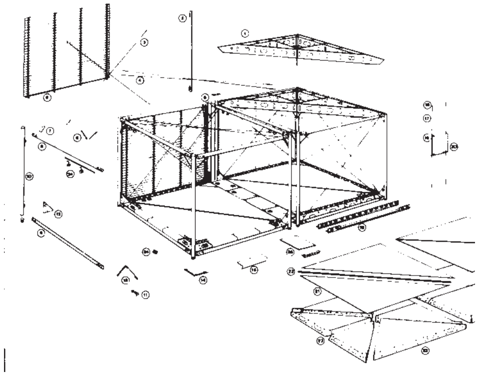


Figure 3.25: left fixed structures, middle partly transformable structure, right totally transformable structure

Thus besides independent physical levels and their materials, another important criteria of technical composition of transformable structures is exchangeability. Thus, it is not only materials but also arrangement of material that creates independent physical levels of technical composition of a building. This process depends on further systematisation of the building and dependencies that are created during technical composition and physical integration (Figure 3.25).

As long as it is acceptable to demolish and landfill materials during transformations of buildings and infrastructure, independent levels are not needed. From the moment when, due to environmental, safety, health, comfort, or economic factors, demolition is not an option, then the levels start to be freed up and their numbers increase.

3.6.2 Systems thinking approach to design transformation

Considering the aspects that play a role in design for change, it is evident that design of transformable structures is a complex issue that addresses aspects of social control, functional and technical composition, and physical interactions.

The main characteristics of previous research that addresses building transformation is that it mainly focused on one aspect of transformation at one time and did not look into interactions between the studied aspect and other aspects that might be involved. (Figure 3.26)

Figure 3.26: Idependently studied aspects of building transformation

The solution of the problem of dependency of building materials within the building can-not be found by analysing only physical relations, functional relations, or relations between the parties involved. Taking into account the number of issues and interactions involved, the problem needs to be put into a larger perspective and should be treated as a systems problem. Therefore, the methodological background for the development of design for disassembly theory in this thesis is based on the systems approach.

The systems approach is somewhat different from conventional forms of analysis. In place of isolating smaller and smaller parts of the subject being studied, the systems approach works by extending its view to take into account larger and large numbers of interactions as the issue is studied.
Assumptions of conventional analysis are that each factor acts independently. According to the systems paradigm, each factor that plays a role in transformation is linked in a circular process to the effect and to each of the other factors. (Figure 3.27). This process can be referred to as a ‘circular process’, or as a ‘feedback loop’. Richmond wrote in his article Systems Thinking that the shift from one-way to circular casuality, and from independent factors to interdependent relations, is a profound one. In effect, it is a shift from viewing the building as a set of static, stimulus-response relations, to viewing it as an ongoing interdependent, self-sustaining, dynamic process.

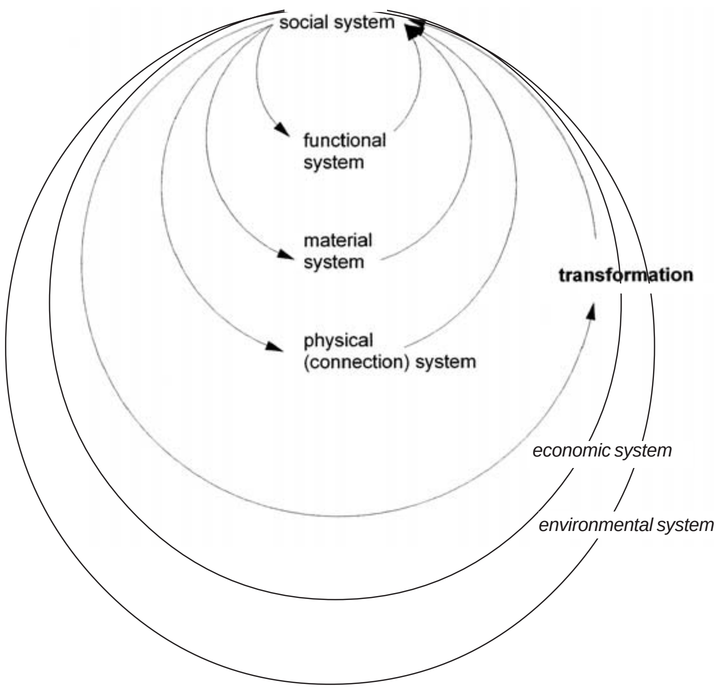


Figure 3.27: Feadback loop relations between the aspects of transformation and environmental, social and economic systems

Besides, some loops will dominate at first; other loops will then take over. Within such complex systems as transformation of building structures, it is considered necessary to think in terms of ongoing, interdependent relations, whose strengths vary over time. To ignore such dynamic interactions between aspects can be characterised as weak. This research focuses primarily on interdependent relations between functional material and physical systems that define the disassembly potential of building configuration and their impact on transformational and environmental systems. Impact on economic and social systems is also discussed. The design of the technical composition of building structures defines their transformation capacity. Therefore, the focus is on specification of design for disassembly aspects within functional systems, material systems, and physical systems in order to be able to set the guidelines for design of transformable building configurations.

Chapter 4:
Further Industrialisation of the building – bridging the gap

Technology is seen in 21st century not as contributing to the destruction of the world but as offering the only key to its rescue.

Richard Horden

INTRODUCTION

Chapter 4 discusses the state of the art in industrial building production and its limitations, in relation to the social and environmental requirements of the 21st century. Industrialised building should not be understood as a goal, but as an instrument to make things possible (and to increase the quality of life). It is this understanding of industrialised building that can play a role in achieving sustainable development. A framework for system development is suggested, which can turn existing industrial production into sustainable practise. It has been argued that this framework provides an opportunity for reaching solutions that correspond with three major sustainability principles:

1. Adaptability to users' needs,
2. increase of material and energy efficiency, and
3. creation of a sustainable economy.

In order to bridge the gap between the conventional and the sustainable, it is necessary to change perceptions regarding the performance and technical composition of industrialised building products. This means that structures should become dynamic and responsive to reconfiguration, a concept associated with reuse and recycling. Such structures are also responsive to the users needs for variation and modification.

Transformation of structures from closed, to open and dynamic, has been defined as a systems problem similar to product structuring in other industries.

The performance of jet engines by Boeing, for example, is not determined by a parts list, but by the integration of parts into one system. The effect that this overall integration creates is the main indicator of an engine's performance. The same is true for building performance. It is not the choice of materials but also the way in which materials are put together that determines the performance of building structures, and accordingly their sustainability.

Therefore, the discussion in this chapter focuses on specification of elements of building configuration, which determine the level of structural efficiency regarding their transformation capacity.

The conclusions of this research are based on insights related to product engineering and a number of building case studies that deal with aspects of technical composition.

4.1 THE NATURE OF MAKING / HISTORIC OVERVIEW OF DEVELOPMENT OF INDUSTRIALISED BUILDING

Besides the specification of fixed and changeable parts based on performance requirements, an equally important aspect of design of transformable structures is the arrangement of parts and their physical integration.
The end-of-life scenarios (as discussed in Chapter 1) possible for a building and its materials, as well as its transformation capacity and their systems, are determined by the physical characteristics of the building. The design of the building configuration determines whether it is possible to achieve environmentally preferable scenarios of reuse and reconfiguration, as opposed to down cycling and disposal of building materials. One can argue that the physical characteristics of a building are a measure (indicators) of building sustainability. Building sustainability depends greatly on the nature of constructing buildings.

Traditional Japanese domestic buildings are builtusing a primary frame of major timber members placed according to the structural requirements of the roof and walls. A secondary frame of timber members is then constructed in accordance with the spatial requirements of the occupants. This secondary frame may be disassembled and remodelled to suit changes in the occupants' requirements, without affecting the primary structure, and without the wastage of building materials that other techniques produce (Itoh 1972, p.43).
Japanese wooden architecture is a complete architectural system in which the expansion, remodelling, removal and reconstruction of buildings is possible according to life styles (Kikutake 1995, p.27).
The technologies applied in these examples show how mechanical jointing techniques and a hierarchy of structure allows for the efficient disassembly of members for reuse. (Crouwel 98).

Technologies that stimulate reuse of building materials have always been practised in the history of the built environment. They occur for several reasons. Sometimes, because of the lack of material: for example, the reuse of wooden beams in Europe in the Middle Ages. Sometimes, for ease of construction: in Renaissance Rome, Michelangelo used stone from the facade of the Coliseum, when building the courtyard of the Farnese Palace (Fitchen 1986), or for reasons of adaptability as seen in the traditional Japanese house.

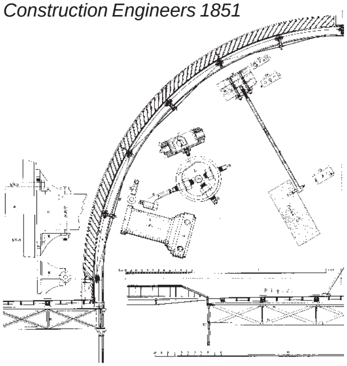
Although design for disassembly has been practised in the past, it has never become a common building practise. It always seemed cheaper and faster to provide integrity of the building by chemical connections and pure mass. Therefore, most buildings, and especially large structures were (and still are) typically made with technologies that result in massive and static buildings, in which disassembly is practised through demolition (a process that produce piles of waste).

The World Exhibition of 1851 announced a new notion concerning physical building integration, which opened the discussion regarding the technical composition of buildings and their construction. This notion was recognised in the construction of the Crystal Palace, where for the first time in Europe, structure and cladding were industrially developed and integrated to form a building (Figure 4.01, 4.02). This first example of a truly industrialised system building is significant by the fact that it illustrates the real potential of system buildings, where standardisation and variation support each other in achieving an optimal materialisation process for the desired design solution (Figure 4.03).

At the same time that Semper developed his four elements of architecture: earthwork, hearth, the framework, and the lightweight enclosing membrane, he classified building crafts into two fundamental procedures:

- Tectonics of the frame in which light weight linear components are assembled, and
- stereotomics of the earthwork, wherein mass and volume are conjointly formed by heavyweight elements

Figure 4.01: Assembly of one segment of the Crystal Palace in London by Joseph Paxton with Fox and Henderson Construction Engineers 1851



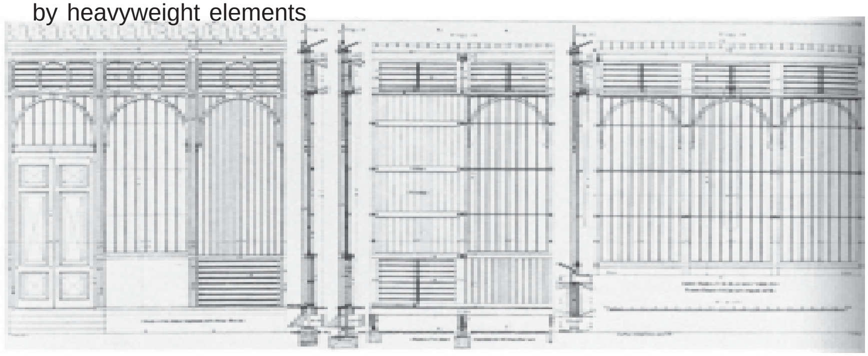


Figure 4.02: Crystal Palace section (US 1995)
Figure 4.03: Crystal Palace façade units

Both the Crystal Palace and Semper's analysis of the elements of architecture were significant in the future development of construction and assembly techniques.

Understanding the distinction between light and heavy structures, and the different life spans of materials later reinforced the tectonic/stereotomic distinction. For example, wood construction displays an affinity for its tensile equivalent, while

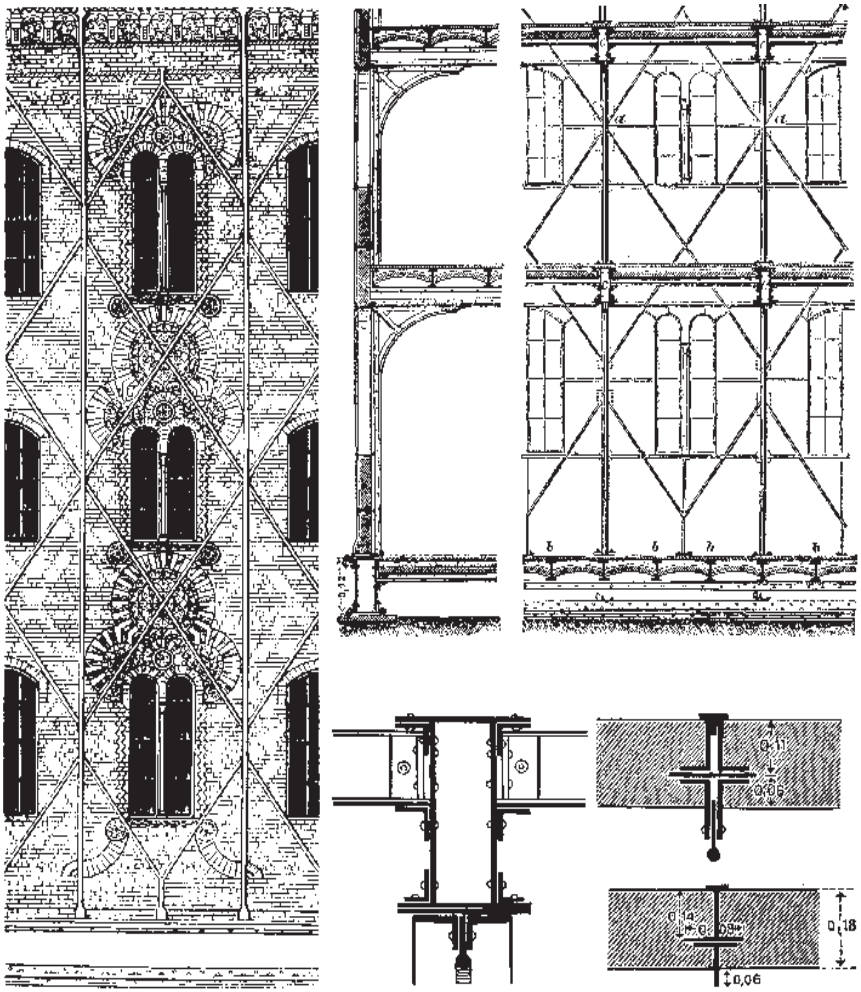


Figure 4.04: An early examples of separation of building materials, Menier-chocolate factory, France, Extention 1871 (SBR 1984)

stonework is compressive material, which can be substituted by brickwork or reinforced concrete. The different life spans of materials become part of the overall integrating process that is the unique role of architecture. Elements with different life spans lead to differential movement, differential durability or incompatible materials.

One can say that the most important industrial development marking the ongoing changes in technical composition of the building was irreversible, connected as it is with improvements in building materials. Once the idiom of a new construction material, such as steel, aluminium, concrete etc. has been translated into building, it brings about revolutionary change in the conception of construction. This leads to a new strategy in defining building performance and its technical composition. Accordingly, the traditional masonry wall began to transform into a light frame wall. Unlike the traditional way of building, where all elements were joined together to form a single mass, the new situation led to a separation of building functions, such as the supporting, partitioning, enclosing and servicing. This notion can already be seen in examples of the Crystal Palace in London, as well as in a chocolate factory in France (Figure 4.04).

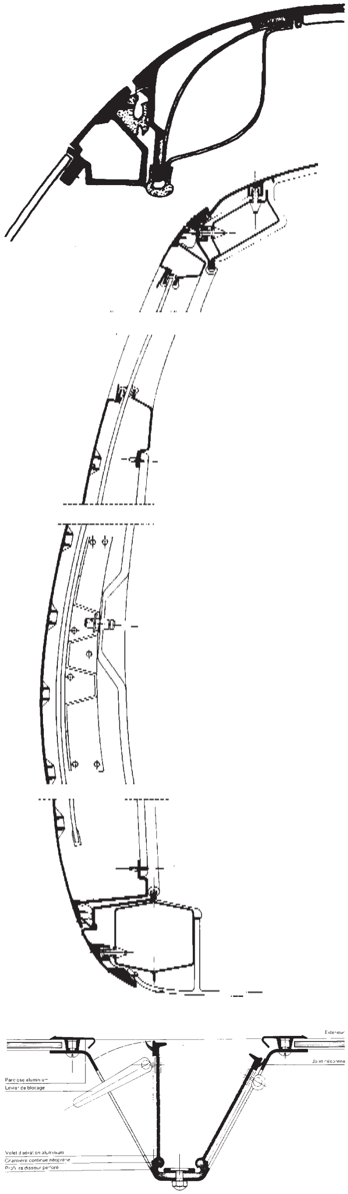
The innovation of corrugated wrought iron sheeting by H.R. Palmer in 1829 provided for the first time a lightweight roofing material that could span between structural elements without the need for secondary timber supports (C. Wilkinson 99). Later, single sheets were replaced by double skins and insulated layers. New shapes become available through the development of glass-reinforced plastic that gave the panels a smooth appearance with two-dimensional curved edges.

At the time of the first generation of industrialised building, the restrictions in the size of components were significant. The diversity that can be created by separation of building functions, represent the most important step towards improvement of building performance and its adaptability to changing requirements.

This led to the development of lightweight flexible structures that make use of high performance steel, wood that can be moulded, optical fibres, plastic, carbon fibres, or ultra-sophisticated glass, which as a result of built in micro air-bubbles provide more thermal insulation in a few centimetres than is currently available in a dozen centimetres of conventional wall. Such expansion of the palette of building materials and their performances, allowed architects to respond in more ways to specific needs of different projects. Design solutions were no longer restricted to traditional materials and techniques and the performance of different functions could be answered in more efficient ways. These new types of structures paved the way for the development of a new architectural design language very different to a pre-industrial one restricted to the use of earth-bound materials.

At the same time, manufacturing processes attracted greater attention, as more elements were prefabricated, transported, and assembled on the spot. With the development of prefabricated techniques, the possibilities of using interchangeable building units became possible. The introduction of neoprene, imported from the car industry by Sariner, solved the problem of connection between independent components, such as glass, concrete panels, plastic, etc (Figure 4.05).

This first generation of industrialised structures has shown the enormous potential of new ways of construction that were somehow put aside in the 20th century.



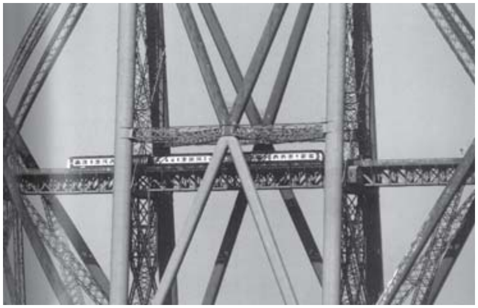
4.05: Neoprene connection details in car (Rice 1995) and building (Jean Prouve 1956)

4.2 THE SECOND GENERATION OF INDUSTRIALISED BUILDING

4.2.1 The first generation of system building

Although industrialisation of building that relies on new technologies has enormous potential for improving the quality of life, major studies of the evolution of industrialised building in the 20th century comes from the field of economics rather than from the history of technology.

Industrialised building built its reputation in Europe in a first half of the 20th century through mass production of housing. Its reputation was based primarily on the trend from the 1950's and 1960's that aimed at construction of low cost housing and improvements of construction processes through enlargement of component size and the prefabrication and repetition of standard elements. The destruction caused by World Wars I and II, resulted in unprecedented need for huge building production that could have only been possible through industrialised production. At this time, all known techniques were brought together to create a system of factory produced components that could be transported to different sites. From an



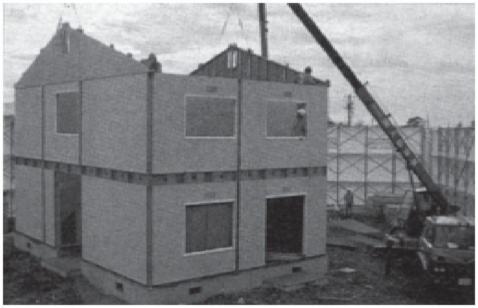


Figure 4.06 Left: Quebec Railway Bridge opened to traffic in 1918; (Rose 1992) right: Prefabricated housing 1980's Japan

economic point of view, perfect conditions were created to produce low cost buildings. For building technology this meant greater quality control, faster building, easier assembly, and better working conditions. But for the built environment, it presumed that identical components would create block after block of identical dwelling units. This produced a low quality environment dominated by concrete panels and boxes.

At that time, mass production was linked with large-scale elements that had direct consequences for architectural expression, and for public understanding of industrialised building. Prefabrication has been seen as a goal in itself, with the biggest challenge being to prefabricate ever-bigger elements for fast assembly, since these can reduce construction cost and time. However, the bigger the size of the standard elements the more dominant they are in the design of a building. Therefore, uniformity was soon attached to this building method that was dominated by a few system producers. It is easy to conclude today that many systems have failed in the past primarily because they were marketed solely under the heading of cost saving and fast construction. This resulted in a uniform spatial and use quality. It is this very limited approach that has resulted in the misconception of industrialisation, and which slowed down its development.

Although industrialisation of building that relies on new technologies has enormous potential for improving the quality of life, the 20th century is marked by great resistance to industrialised approaches to building. This is why buildings are still dependent on conventional building methods.

One of the main reasons for the misconception of industrialised building is because industrialisation involves standardisation at some level. Therefore, the general feeling is that industrialisation involves uniformity, although this is not necessarily the case.

"There is an explosion in design, an explosion in variation based on standardisation. Many people think that if you adopt a certain form you actually restrict yourself. But if you do it well, you adopt a certain form to by freedom, which is what you do when you learn to play the piano..." (B.Mulder00) This can be clearly seen in the examples of the first generation of industrialised structures that experimented with the industrialised way of construction, such as the Crystal Palace, the Eiffel tower, or steel bridges. They all illustrate new notions in construction that have adopted an industrialised way of making structures based on standardisation. These structures have proved that industrialisation does not result, per definition, in uniformity.

"... At the end of the 20th century we are creating generic infrastructures. You don't know how it works, but it allows you to do something else, like money systems, like legal systems, like roads. So generic in a sense means that it is always here, it always operates ... by standardisation by the fact that I can remotely control them, these structures allow for immense variation."

Although the first generation of industrially produced structures clearly illustrates this statement of Bert Mulder, the non-acceptance of system buildings by the public comes from the observation of the second generation of industrialised structures, which is the result of post-war reconstruction in Europe.

That is why building construction is still dependent on more traditional construction methods.

If one looks at the building site today one cannot believe that we live in an age of space travel (R. Horden 00). The thousands of building parts needed for erection of a building are transported into congested city centres of Amsterdam, London, Paris, etc. where construction work is carried out under dangerous conditions and is exposed to the elements. Horden also writes on building with systems: "Demolition work and the erection of a seven-story office building in the centre of London take about 18 months to complete, subjecting not only immediate surrounding to noise, dust and increased traffic but imposing the burden on the entire infrastructure of the city." Besides the direct negative impact, such building methods create negative impact on the environment, due to lost materials and energy and accumulation of waste.

If one would understand the true potential of industrialised building, the way would be open to bridge the gap between human prosperity and environmental efficiency,

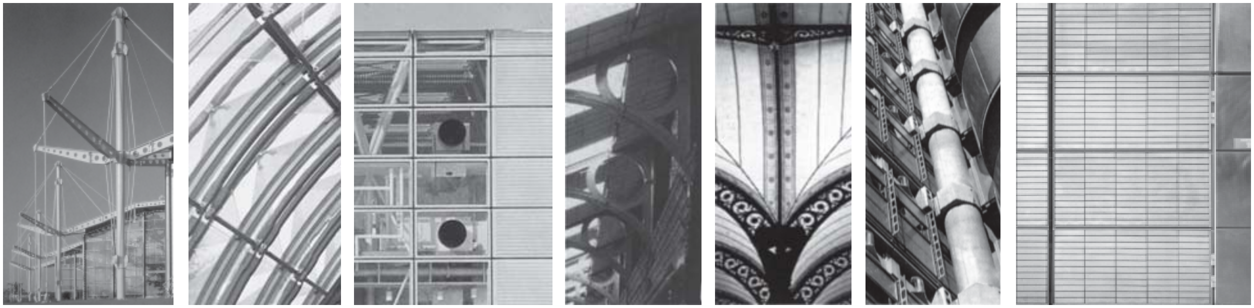


Figure 4.07: Potential of the industrialised building structures; From left to right: Renault -center by N.Foster, IBM pavilion by R. Piano,Sainsbury Cetre by N.Foster, Berlage, Berlage, Lloyd's of London by R. Rogers, IRCAM Building by R. Piano

which is the essence of a sustainable future.

The potential of industrialised building however is on the other side of uniformity. It is industrialised building that offers not only conscious use of building materials but also diversity and adaptability to individual preferences (Figure 4.07).

4.3 THIRD GENERATION OF INDUSTRIALISED BUILDING

4.3.1 Towards the third generation of industrialised structures

In place of costs, the quality of life (in the context of sustainability) should be understood as an integrating value of the overall system building. (R. Horden 00) The structures that provide a better quality of life in the future are the structures that make efficient use of earth resources while providing adaptability of structures to users' needs. The image of industrialised building was for too long dominated by the monopoly of producers of standard systems primarily marketed as cost saving building systems. Such systems are standardised, based on the short-term view of market need, but did not consider full life cycle aspects of the system. The restrictions of these systems are not only that they are not designed for reconfiguration and disassembly, but that they are not the result of real-time optimisation of project requirements, costs, and available techniques. Standard systems and components capture and formalise some of the knowledge on which inventors draw. W. Mitchell states in his article Artefact grammars and architectural invention "Considerations of developments in material science and fabrication technique is never a definitely finished task, since technological developments can always extend the ranges of available materials and fabrication techniques,

and the exigencies of economic and social conditions can constrain what is actually possible in practice at a particular moment in a particular context.”
If we examine the way that building products are made we find the characteristic product vocabulary of sawn and turned timber, rolled and cast steel, extruded and moulded, plastic, and so on. That means that there are practical fabrication constraints so that the standard product vocabulary (list of products) is only one small subset of the set of all possible combinations of shapes and materials.

What transforms clay into Piano’s IRCAM building, the Beurs by Berlage, or the Central Station in Amsterdam is the architect’s invention based on knowledge about fabrication and assembly techniques that transform building materials into a desirable building design. The pioneer in such design engineering has been Jean Prouvé. Figure 4.08 shows the manufacturing of façade panels, which were designed by Prouvé and the aluminium industry.

The misunderstanding that was created around the second generation of industrialised building was based on the fact that designers fulfilled their design tasks by using finalised systems that were offered by the industry. These were usually closed, static systems optimised for low costs, fast production and fast assembly, rather than for the individual preferences of a project, or for the disassembly of their parts. Instead of designing with standard systems, architects should adopt an industrial way of making buildings. Instead of designing with standard systems, architects should design with industry. The aim of building is not to develop design solutions around standard systems but to design systems that are result of the performance requirements of each project.

There are architects and architectural groups such as Future Systems, Richard Rogers, Norman Foster, Nicholas Grimshaw, Richard Horden, Jean Prouvé, etc. that provide novel examples showing how industrialised building could be something other than the result of a monopoly of system producers controlling costs and design solutions. They illustrate that there are different ways of making buildings with industrialised products, with the close co-operation of architects, industry, advisors, and contractors.
Thanks to developments in robotics and automated assembly, production techniques are developing so fast that currently different forms and sizes of building

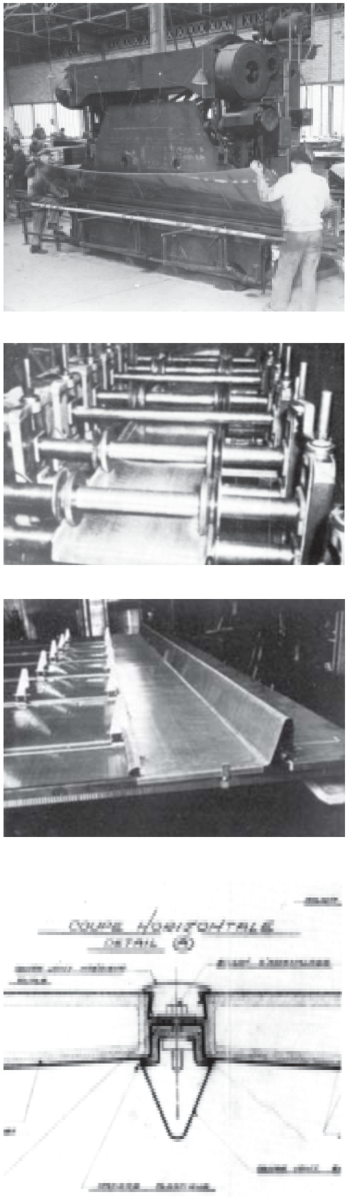


Figure 4.08: Manufacturing of fasade components Jean Prouvé 1950’s.

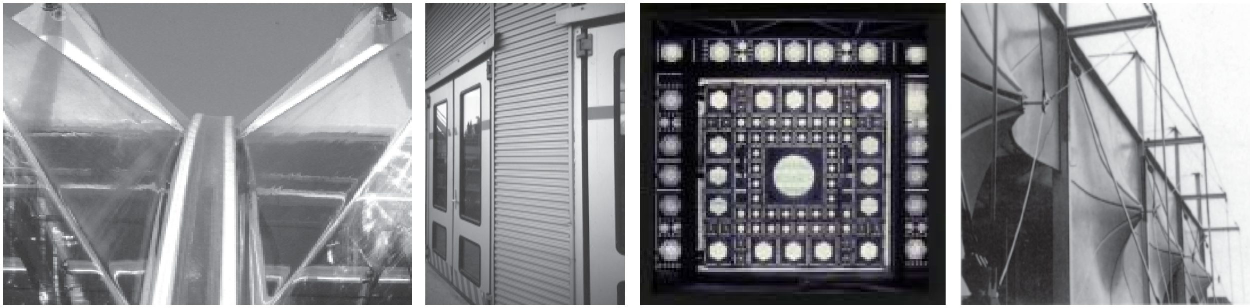


Figure 4.09: From left to right: IBM Pavilion Renzo Piano, Housing project Jean Nouvel, Arab Institute by Jean Nouvel, Italian Pavilion at Osaka Expo by R.Piano

components can be produced without costly adjustments to production lines (Figure 4.09). This adds to the enormous potential of the third generation of industrial system building.

It is not about nuts and bolts, but nuts and bolts make it possible, so it is not the technology as an end in itself, it is a mean to an end. (Sir Norman Foster)

4.3.2 The potential of the third generation of industrialised system building

The third generation of industrialised building will make use of the electronic age in which we live.

Recent developments in information and communication technology give enormous boost to the further industrialisation of building and system development. Restrictions in size and fixed assembly procedures are becoming less of a problem. The major challenge of manufacturing has become how to deal with complexity, uncertainty and change, as product life cycles become shorter and multi-science products start to emerge that include IT, biotic, chemical, and mechanical electrical technologies. Taking into account the need for conscious handling of material resources and design of intelligent and re-configurable systems, one can say that the value content of manufactured artefacts is relatively small compared to the value of the service and knowledge content associated with an artefact. Therefore, the business focus of manufacturing should be switched from the production of tonnes of material to the design of its end performance. This should increase the market value of materials, and the competence of manufacturing industries.

Research indicates that manufacturers will compete in the future not based on the ability to make specific products, but on their competence to develop products customised to specific customer needs. This approach supports mass customisation while taking into account environmental issues. Under these circumstances the building industry will have to focus on approaching the end user by making steps towards mass customisation, and by rethinking its position

An attempt at such an approach is the program of the Dutch Government called IFD (Industrial, Flexible and Demountable) Buildings. As a part of this program number of customised housing concepts have been developed in past 5 years. Van den Thillart pointed out in his PhD these “Consumentgerichte industrialisatie in de woningbouwsector” that the reason for the growing interest in customisation of housing is in a fact that housing market in the Netherlands is not dealing with the problem of quantity, but quality. As a result the number of developers, manufactures and contractors that are involved in customisation of building industry and upgrading of industrialised building components that are more targeted to the end user is grooving. Some of these are developing company ERA which developed concept called Personal Housing,(IFD 2000) HBG took over smart house designed by Robert Winkel (IFD 2000), Zondag Bouwgroep developed “gewilde wonen” based on the concept of C. Weber, Nijhuis developed Trento etc.

The aim of customisation is to upgrade industrialisation of housing by involving users in project development from the beginning of developing process. They also make a use of ICT for communicating the user’s wishes. Very often software tolls are developed that offer number of options so that potential owners/users could choose from few different spatial typologies, size of the house, material and culler of the façade, type of the kitchen and bathrooms etc.

However, the evaluation of “wilde wonen” neighbourhood in Almere where 22 project were built as industrialised and customised projects indicate that in most cases once the ownere/usere has made a choice, rather fixed technical systems are put in place which do not support adaptability, replaceability or reuse of building components. In other words most of these customised building systems do not offer a freedom of choice to the second user/owner of the house. However unlike previous systems developed in 70’s this customisation is driven by market demand, and one can assume that the aspects of transformation and recovery of building materials will be integrated in the next generation of customised housing concepts.

Besides IFD program was supposed to stimulate all parties involved in construction to implement Industrial Flexible and Demountable technology.

Although D was part of the program, the design solutions found in most nominated projects were rather simplistic. Nevertheless, this program gave a positive impulse to individual development of flexible systems, which are an important aspect of IFD building. Systems worth mentioning are floor and electrical systems as that have solved some problems of the fixed integration between structure and services. Some of them are Corus Star-Frame floor, Infra+ floor, Wing+floor, Kabelweg system, KISS system and many others.

Yet, the real problem that these systems face is of a practical nature, such as application (*and integration of these systems into a total housing system)* of the system. Experience with IFD projects has shown that the real problem of sustainable construction does not lay in product development itself but in development of an integrated design concept that makes use of flexible, industrial, and demountable systems. In other words, a systematic integration of issues from use scenarios to the manufacturing of products, which would fit in use scenarios, would be needed in order to see IFD as an alternative to the way we built today.

Another example of the third generation of industrialised building can be found in the United States. An example worth mentioning is the work of Jennifer Siegal from California who is developing a precision made home concept. The idea is to invite known architects such as Frank Gerry and Steven Holl to design housing lines, which address different needs and budgets. Once developed, these lines will be totally factory produced. Siegel herself is famous for her modular Portable House and Swellhouse (Figure 4.10). (Lecture by Jennifer Siegel, Whitney Museum, New York, February 2005)

Figure 4.10: Left the Office of Mobile Design, right the Swellhouse

The Modular Portable House is completely assembled at the factory and arrives ready to install. Buyers can chose from ten floor plans and two sizes depending on their needs and budget. The prices range from $79.000 to $125.000. The Swellhouse, on the other hand, is customisable residence made up of panellised walls on a steel frame. Components are shipped and assembled on site.
However, such concepts have big restrictions because architecture is context dependent and structures need to be flexible in order to be adapted to site requirements. That is why such concepts are manly used in rural California where are no strict restrictions regarding the size, orientation, relation with surrounding structures exist. An interesting example where another approach to modular building is given, is one from the New York City firm of Resolution:4 Architecture. Instead of expecting manufacturers to adapt to their ideas, they decided to design houses that could be built using established factory procedures. Based on that concept they developed six modular housing typologies. Several variations exist within each typology, and each one can be customised and combined with other modules, form other typologies, to create a house tailored to its site and client.

Figure 4.11: (Customized modular typologies S.Freeman 2005) Each modular home represents adoption of different modular typologies.
The Mountain Retreat(above) is a cross between the Lifted Bar and Two-Story Bar
The Retreat House above left) is a customised blend of the Offset T, 3-Bar Bridges, and Two-Bar Slip.(artcle custumize modular typology byMeghan Drueding, january 2005

Such customisation does not come cheap, but it costs significantly less than pure custom, site-built projects. A customised modular residence cost $175 to $200 per square foot while the site-built custom home, tops out at $300-$350 per square foot. Moreover, the costs of Resolution 4's modular homes could decrease over time. (Figiure 4.11)
Considering the three evolutionary steps of the industrialisation of building discussed above, the nature of building has been evolving from careful construction work on building sites, to the assembly of custom-made elements made off-site. One can also notice a slow transition from closed/static to open/dynamic systems that are composed of independent subsystems and components whose performance can be remotely controlled.

The main potential of industrialised approach to making buildings can be summarised by the following:
• Freeing up of many of a building's functions and altering them from fixed to less dependent conditions,
• greater quality of buildings
• greater match between requirements and materialised solutions,
• greater quality of life (that match buildings to individual preferences),
• better control and more efficient use of resources,
• greater possibility to reconfigure structures according to new demands,
• diversity,
• development of assembly/disassembly techniques, and
• extension of the designer's vocabulary, expressed in combinations of different, and materials for the building's structure.

These aspects correspond to the goal of sustainability, which is to provide structures that consume the minimum amount of material and energy over their life span while answering to the specific need of users — thus celebrating diversity.

The evolution of industrialised building through introduction of prefabrication, the concept of interchangeable components, and the developments toward customisation of industry indicates that it has the potential of becoming a secure partner in achieving sustainability goals. Considering a fact that sustainable development involves consideration of the efficiency of material use through the whole life cycle of products, the main barrier to the sustainable manufacturing of building products is in a limited role and responsibilities that manufacturing industry has during a building development. In other words manufacturing industry of building systems should take responsibility for the whole life cycle of their system including operation, maintenance, disassembly, reconfiguration of the system and reuse and recycling of its parts. Herewith the building industry could use experience from other product industries that have already integrated the whole life cycle approach to the product development through the concept of design for disassembly. However, in order to develop building systems targeted to meet the requirements of users need for adaptability and social need for transformation of buildings, its structures and materials without negative environmental impacts this goal is difficult to achieve without closer cooperation between architects and manufactures. This because of the fact that the relationship between the "what" has to be constructed and "how" is becoming extremely changeable and dynamic. Only through close cooperation between building industry and architects would it be possible to integrate and optimise processes, technique and use of materials in order to answer the diversity of ever-growing number of requirements on the built environment. One of the key step that has to be made in order to use the potential of (industrialised production in a sustainable construction, that relays on disassembly and recovery of single material, is to provide a design strategy that will integrate aspects of spatial, structural and material transformation into building systems and components.

In order to be able to provide a framework for design of such sustainable buildings and its systems, it is necessary to assess performance characteristics of a building's configuration(s) regarding transformation whose aim is efficient use of single material. The design decisions regarding technical composition of configurations determine the performance of the structure, as well as the end-of-life scenarios for the building and its materials. Ultimately, design for disassembly aspects that can be accounted for above mentioned transform are directly related to configuration design.

4.4 CONFIGURATION DESIGN OF TRANSFORMABLE BUILDING STRUCTURES

To build, according to Schinkel, is to join different materials into a whole, corresponding to a specific purpose of the building (UofS 1995). This definition clearly demonstrates that this goal is a fundamental principle of all building. Thus the goal defines the boundaries for development of a building and its constituent parts.

Configuration is regarded as the process of creating an arrangement from a given set of elements by defining the relationships between selected elements that satisfy the requirements and constrains. (Yu 1995)

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 elements and with different design decisions. The set of relations and elements 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. Knowledge of the physical state of the structure is crucial for the exploitation, transformation and disassembly of the building.

4.4.1Design domains of building structures /configuration design

Design of every building configuration can be presented throughout three main

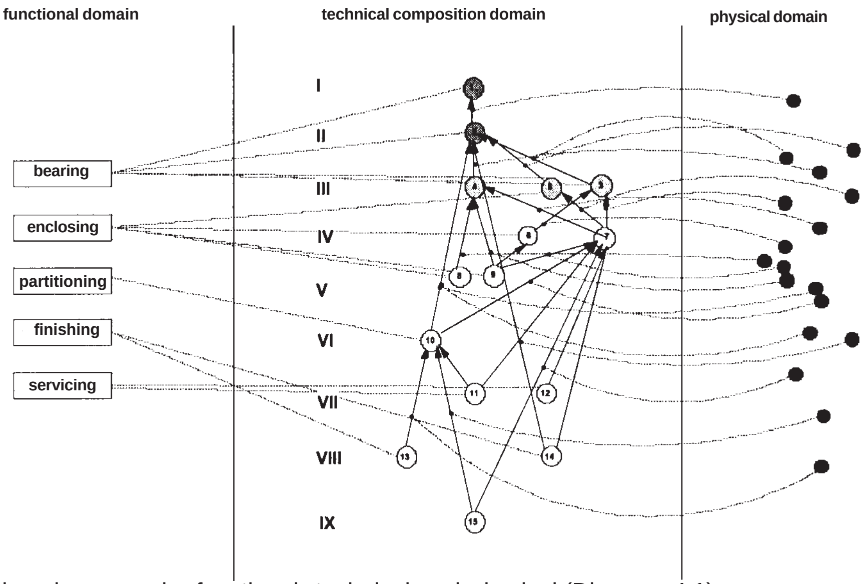


Diagram 4.1 Relations between functional, technical and physical domain

domains, namely: functional, technical and physical.(Diagram 4.1)

- Functional assembly is a description of the functionality of an assembly. It comprises decomposition of functions.

  The assembly in this domain is defined as a structure of functions where a function is defined as an ability to create effects. For example, functions on the building level could be to carry a load, to isolate, to divide, to supply etc. The functional domain is strongly related to the purpose of the assembly. The specification of the requirements is an important input for this domain. The design of transformable configuration starts with functional decomposition and its allocation through different components. Showing only the location of the inputs and outputs of the assembly as a whole, and ignoring the internal chains of connections that relate inputs to the outputs of the assembly, can accomplish functional abstraction. Mitchell defines functional abstraction as a representation that focuses on what is accomplished by an assembly, while ignoring the details of how it is done.
- Technology models focuses on composition of the building or building products that are carriers of functions described in the functional domain. It defines use of technologies and methods in order to specify principle solutions for composition of the structure. As with the functional domain, the decisions on technology domain are taken up one building level at the time.

- The physical model is a consistent description of the physical relations within an assembly through the description of parts of assemblies and their relations. It is directly related to the manufacturing and construction of an assembly and should guarantee easy assembly/disassembly operations without compromising the quality of technical composition and functionality of the assembly.

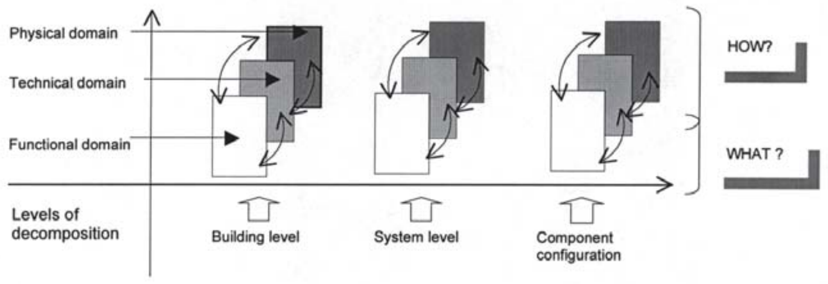


Diagram 4.2: Domains of configurations on all level of building technical composition

Although these domains can be distinguished, they cannot be separated in the decision-making process. Design decisions regarding the functional domain cannot be made independently from the technological and physical domain. This means that the functional decomposition cannot be performed unless at least some knowledge is available regarding the realisation of the function. In other words, the “what” of the design (form and function) is developed in coherence with the “how” of the design (the means such as type of assembly and its physical integration). (Diagram 4.2) This plays an especially important role in the design of decomposable structures. For example, the building functions could be allocated through independent building systems. On the other hand the internal composition of the systems, just as the physical relations between the systems, could make the building structure unsuitable for disassembly. Consequently, changes to the structure in the later phase of the design could have consequences for the quality of the overall design concept.

Design domains of configuration correspond to the elements of configuration. For example, the functional domain corresponds with material levels, the technical level corresponds with the hierarchical arrangement within a configuration, while the physical domain corresponds with an interface design. The elements of configuration are discussed later in this text. The decisions made in each design domain regarding the elements of configuration, determine the performance of the configuration.

4.4.2 Theoretical background for the assessment of configuration performance

Each building can be defined as a hierarchical arrangement of all its elements. Therefore, this internal arrangement determines the structure of the building and the ease or difficulty of a building's future dismantling. A building does not necessarily exhibit one single structure, but hides within its structure of sub-systems and components, different structuring principles that fit the building for construction, service, and deconstruction. Therefore, the sub-assemblies of the building, their internal composition and the way in which they are assembled together determine the behaviour of the building and its structures configurations. It is impossible to talk about unstructured buildings, but we can talk about weakly structured buildings that have the characteristics of being difficult to assemble, difficult to repair, difficult to change, or difficult to disassemble.

The three levels of decision-making regarding technical composition of building assemblies are:

1. Specification of material levels,
2. hierarchy and arrangement of parts, and
3. physical integration of parts.

In order to provide a framework for the assessment of configuration performance regarding disassembly and transformation, three variables will be considered (table 4.1):

1. Variables representing the elements that define the typology of configuration: the way that these specified defines the performance of a system configuration,
2. variables used to measure system's performance: these are the criteria used to evaluate configuration regarding transformation based on disassembly , and
3. variables specifying the performance indicators: these represent their transformation capacity.

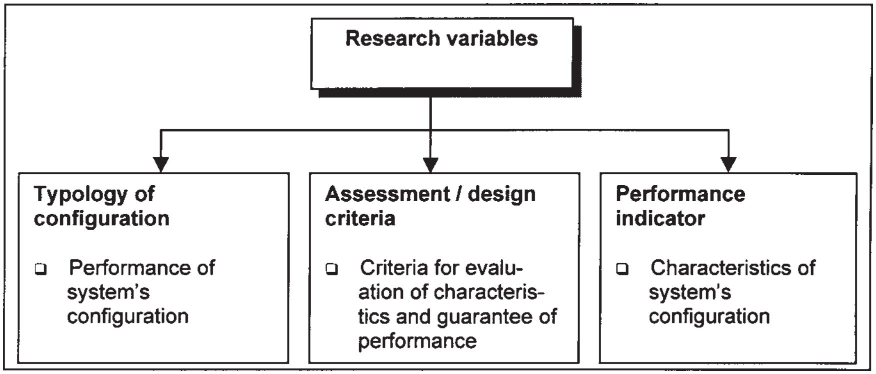


table 4.1: Research variables regarding the assessment of configuration performance with respect to disassembly of its parts.

4.5 ELEMENTS DEFINING TYPOLOGY OF CONFIGURATIONS

Key determents of the successful configuration of systems building are the ability and ease of component and material recovery, and systems adaptability. Therefore, it is necessary to develop a design approach that efficiently manages the end-of-life of buildings and their parts.

An essential part of this approach is to understand how structures work and how they can be reconfigured and modified. One way to put light on this issue is to analyse elements that define a typology of configuration.

Configuration in building design means creating an overall solution out of elements. Obviously, 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 a configuration, since each configuration is a representation of materials and their relations.

Therefore, typology of every configuration is defined by three elements of configuration that stand for previously specified three levels of decision making with respect to technical composition:

- Material levels: This is element of configuration design that deals with functional decomposition and allocation of functions into separate materials, which respond differently to changing conditions. These materials have separate lives, which lead to differential movement, differential durability, or incompatible materials.
- Technical composition: Technical composition deals with hierarchical

arrangement of the materials, and relations between materials. consists.

- Physical integration: Physical integration deals with interfaces that define the physical integrity of the structure.

Configurations are sets of materials and their relations, while materials correspond to a desired function. The fundamental question of design for transformable structure is what kinds of materials and what kinds of relations are regarded. Specification of these three elements of configuration determine the configuration's typology, and therefore the transformation capacity and disassembly potential of the structure.

For this reason three elements of configuration are defined and shown as independent variables in this research (Table 4.2). The performance of a particular configuration with respect to disassembly (and transformation of the structure) can be measured by two criteria for disassembly: independence and exchangeability of materials. In other words, a 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.

Performance indicators of transformation can be assessed by analysing three elements of configuration using two criteria that determine disassembly potential

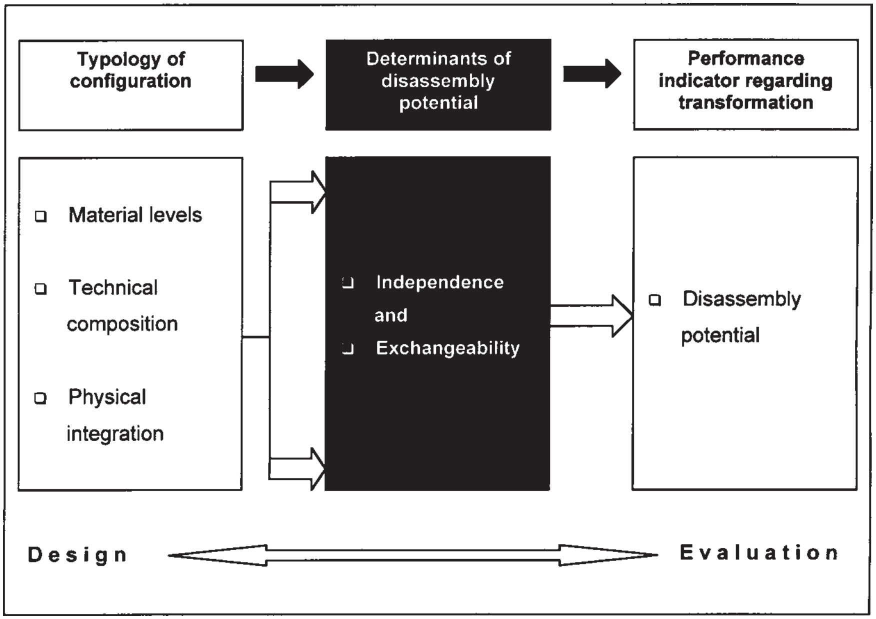


table 4.2: Conceptual model of design for disassembly and its evaluation

of configuration materials. (table 4.2) This research argues that such conceptual model can be used in two directions : as design guideline and evaluation of transformable structures that relay on disassembly. When considering independency and exchangeability of building materials three elements of configuration design can be optimised during design process in order to provide higher disassembly potential of designed configuration.

4.5.1 Impact of independence and exchangeability on specification of Material levels

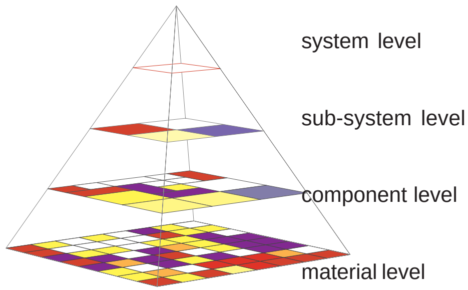
Design of configuration begins with the systematisation of materials that provide a certain function.

Industrialised building methods offer a possibility to cluster group of parts into workshops. Later this group of parts is assembled as a sub-assembly on a building site.

The sub-assemblies exist on different levels of technical composition of building. Such levels are called material/physical levels in this research. A sub-assembly is a cluster representing building elements that act as one independent building section in production and assembly/disassembly. The design team defines sub-assemblies based on required performance, production flexibility, system design, and geometrical or mechanical criteria. Elements are seen as the basic parts that form the lowest level of building sub-assembly. This is called the component level. 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).

Such specification of building is based on a top-down systems approach. The objectives of subassemblies define their function. Creating a subassembly that can fulfil this function is what the systems approach is all about. Constraints of the system limit its operation and define the boundary within which its constituent parts are intended to operate. 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,



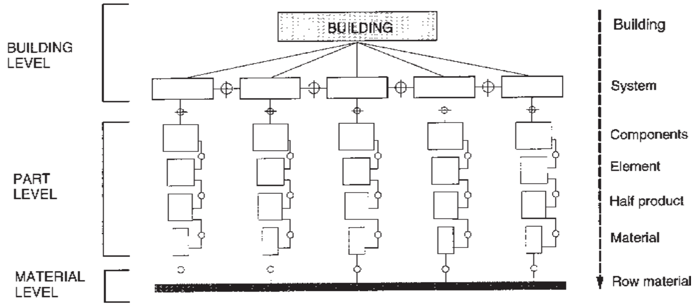


Figure 4.12: Left Hierarchy of material levels in building. Systems approach to the building
Figure 4.12: Right Systematic integration of material levels in the building

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. (Figure.4.12)

Specification of the material levels provides the greatest transformation capacity if each function and sub-function corresponds to an independent assembly and sub-assembly. Static configuration is represented with few material levels because few functions are fused into one fixed material level. However, different parts of the building have different functions and, accordingly, different use and technical expectancies. Therefore, in attempt to design open/dynamic configuration effort should be made to separate different building functions by use of separate sub-assemblies for each function. One sub-assembly is a group of parts with the property that the parts in the sub-assembly can be assembled independently of other parts of the structure (Figure 4.13).

For example, one façade system can be structured following the pattern of functional decomposition into sub-functions, such as enclosing, finishing, isolating, water protecting, and bearing. Further on, sub-functions are allocated through the independent elements that are arranged into components and all together to form a particular façade system. (Figure 4.14 right) The components are the materialisation of sub-functions, which may have different changing rates.
By decomposition of façade into number of independent components the façade

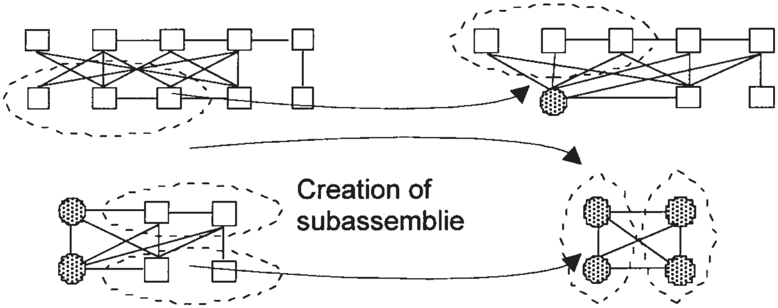


Figure 4.13: Clustering of building materials into independent functional and assembly clusters – the figure illustrates the process of transformation of configuration from maximal interrelation between separate materials to their systematisation into functional and assembly clusters. Such systematisation plays key role in diminishing the number of disassembly sequences on the site, which is often a bottleneck for disassembly.

system becomes more flexible because it can easily be reconfigured / modified according to the new requirements regarding provision of light, insulation, position of openings, façade finishing etc. At the same time, the potential to reuse components has been increased. This is one of characteristic of open façade systems (Figure 4.14.right). Development of such systems takes into consideration both a short-term strategy related to the adaptation to future use, and a long-term strategy related to the end-of-life scenario of building components. On the other hand closed façade systems integrate most of their systems functions into one composite component. Figure 4.14 left illustrates such a concrete façade system, which has been recently developed for the construction of a number of housing towers in Hong Kong (Figure 4.14.left). Such configuration lacks a transformation capacity and cannot be adapted to new requirements. Furthermore, at the end of a system's use life the only end-of-life scenario is demolition and down cycling of material since all materials integrated into this system form one fixed physical level.

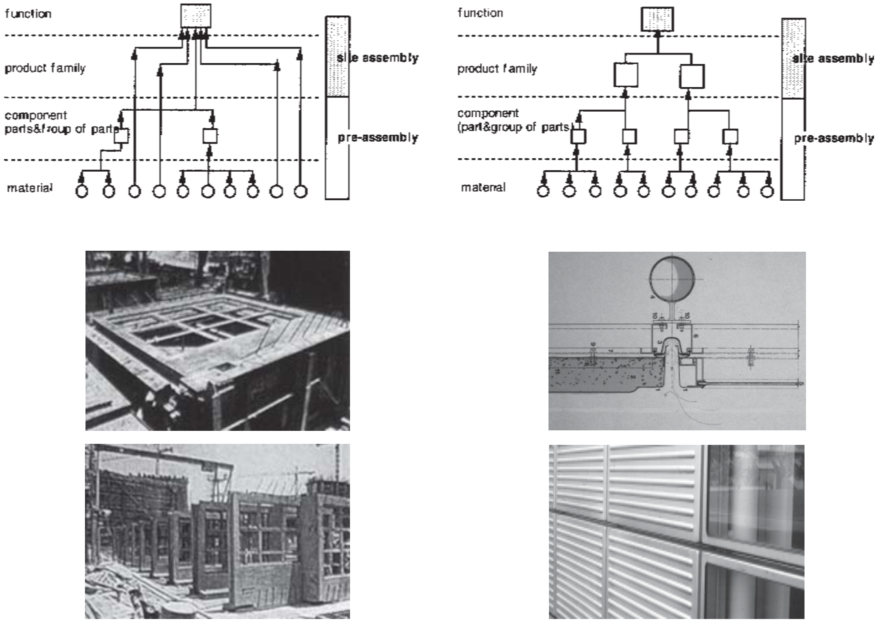


Figure 4.14. left: closed/static system configuration of Harmonie project in Hong Kong, as a result of lack of functional decomposition
Figure 4.14. right: open system configuration of facade system designed by Foster, as a result of functional decomposition of façade system that was flowed by development of independent sub-assemblies

Figure 4.15 a

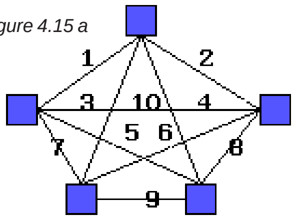


Figure 4.15 b

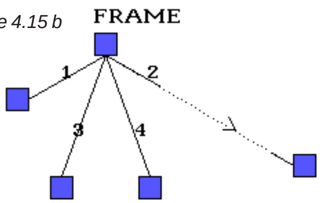


Figure 4.15a,b: diagrams represent transformation of hierarchy of building elements from closed to open hierarchy (Kapteijns at all 1998).

4.5.2 Impact of independence and exchangeability on specification of hierarchy of parts

Dependencies between building components are often the reason for demolition and costly renovation of buildings. Most projects focus on assembly, but once a building is constructed, it starts its life through different phases of use, which require maintenance (finished assembly being removed for service reasons), and modifications (functional assembly being removed for adaptation reasons). These aspects are usually not taken as a design criteria for buildings. Rather, all building components are put together in a manner that reduces construction costs and time, without taking into account “what happens after they are built” (S. Brand).

Therefore, conventional buildings can be characterised by complex relational diagrams, which represent the maximal integration of all building elements and materials into one dependent structure. The evolution of building configuration from fixed to dynamic is represented by the transformation of complex relational diagram into an ordered pattern of relations. Thus it is not only specification of independent material/physical levels along the functional decomposition but also the arrangement of materials that accounts for their independency and exchangeability.

Research of OBOM conducted by J. Kapteijns addressed the issue of arrangement of parts in 1998. This research indicated that five elements can be connected by creating separate relations between each element. This result in a great number of relations and interdependencies. (Figure 4.15 a) Contrary to this, five elements can also be connected by one intermediary, which acts as the base element for other parts. In such a way the number of relations and interdependencies is minimised (Figure.4.15 b).

One can assume that a building structure can be defined by number of independent assemblies, and that each assembly of materials would have one intermediary element that would act as a base element for other parts. Under such circumstances building structures could be defined through relations between the intermediaries that are placed on different levels of a structural integration/ technical composition (Figure 4.15c). On the building level the load-bearing structure is the base element for other sub-assemblies, such as façade, roof, floors, installations, partitioning walls, etc.

On the sub-assembly level such as the façade, an element such as a sub-frame can be the base element for all other parts of this sub-assembly, such as windows, ventilation openings, doors, insulation finishing elements, etc. Further more the window would have base element, which connect all parts of the window such as glass, window knob, sunscreens, etc.

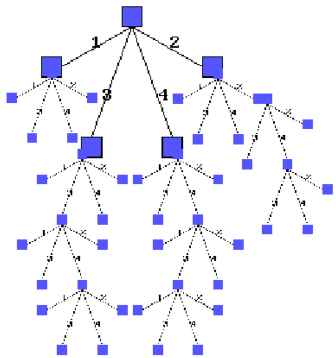


Figure 4.15c: Diagrams representing transformation of hierarchy of building elements from closed to open hierarchy(Kapteijns at all 1998).

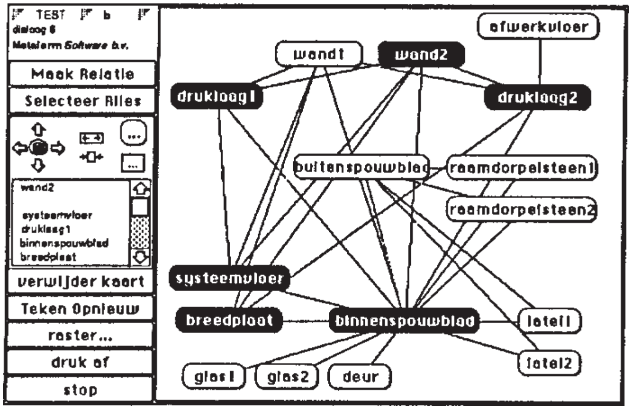


Figure 4.16: Relational diagram representing one static structure(Kapteijns at all 1998);

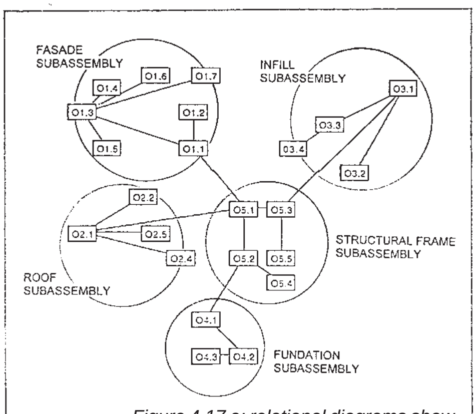
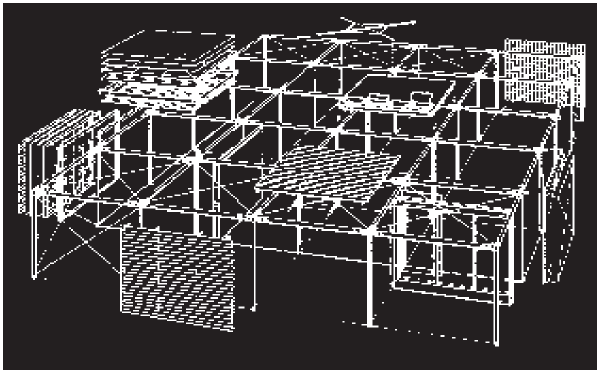
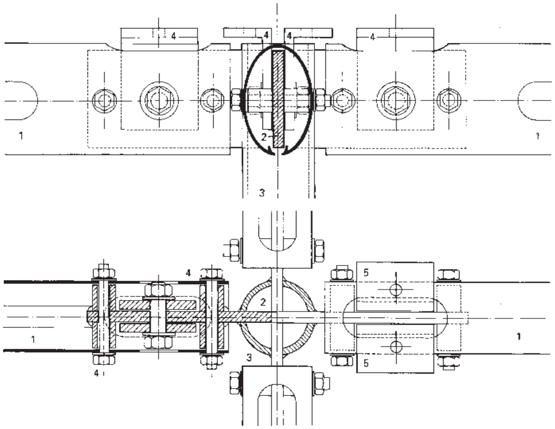


Figure 4.17 a: relational diagrams show relations between components of Yacht hous on building level and system level by R. Horden





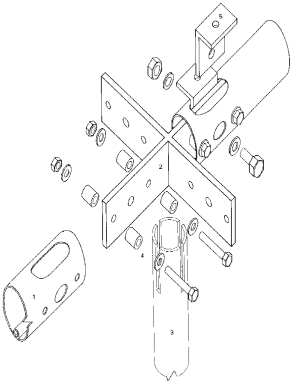


Figure 4.17 b: Details of the yacht house by R. Horden (Brooeks 1998)

Such systematisation of building through base elements and their connecting parts, gives a structure a potential to better control use of parts of the building, and total disassembly at the end of the design life of the building. An example of such configuration is the design of Yach house by R. Hordon (Figure 4.17 a and b).In such dynamic configurations, sub-assemblies represent independent sub-functions of a main functions as façade, roof, structural frame, infill and foundation. Although there are few subassemblies per building function the subassemblies representing one function do not have relations between each other nor do they have relations with subassemblies representing other functions. Subassemblies are connected only to a base element, which is manly in a form of a frame (façade frame, roof frame partitioning wall frame). Further to this an intermediary element has been developed in order to separate frame of roof subassembly from the elements of load-bearing structure (figure 4.17 b). The same pattern can be recognised within sub-assemblies. For example in order to provide easy mountable and dismountable load bearing structure an intermediary element has been developed which separated post and beam elements (see 3D detail in figure 4.17 b). Thus, in order to evaluate the disassembly characteristics of configurations, two types of relations have to be considered: one between assemblies, and one within assembles. Both relations can be analysed through diagrams presenting relations between independent materials.

A relational diagram informs us about the dependence between sub-assemblies and number of relations. A differnce between static and dynamic configuration is shown in figures 4.16 and 4.17a. However, in order to evaluate the real transformation capacity of the structure, more types of relations need to be analysed, for example, assembly relations, life cycle relations, type of relations regarding the connections, etc. Not all of these relations can be presented in one relational diagram. Thus, the total view of the structure is the sum of all types of relations between the elements related to their reconfiguration and disassembly.

4.5.3 Impact of independence and exchangeability on specification Interfaces - Physical integration

The third aspect of every configuration is the physical integration of parts within a configuration (Figure 4.18).

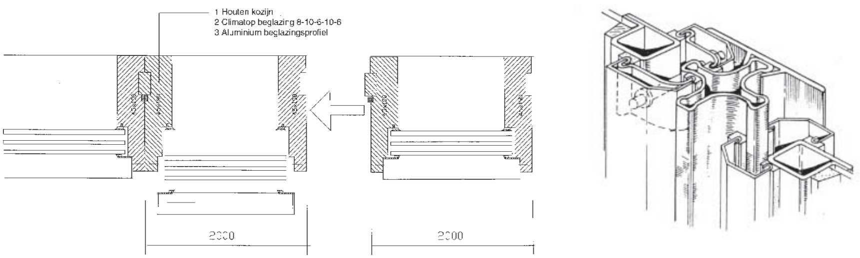


Figure 4.18: Two principles of physical integration of parts

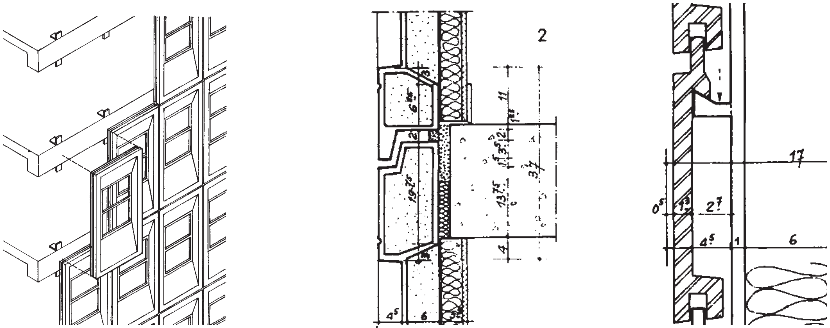
The aspects, that determine physical integration between the elements are: type of connection, the geometry of elements edge, and the assembly sequence.
Static configurations are often recognised by chemical connections, geometry which results in stuck assemblies, and accordingly with dependent assembly sequences.
Dynamic configurations favour intermediaries between connected elements with accessible fixings that one can be replaced without affecting the other and mechanical
connections. Further to this the simple geometry of edges and independent assembly/disassembly sequences, are a part of dynamic configurations.
An important goal of physical integration is to reduce the number of assembly sequences of building elements, especially during replacement procedure.

4.6 DEPENDENCE BETWEEN THE ELEMENTS OF CONFIGURATION

The design decisions regarding the assembly determines the entire service life of the building and its materials.

Key components of every configuration (composition) of a design are defined in previous text as its functional, technical, and physical composition. Accordingly, the main design components of transformable and deconstructable configurations are: functional, structural, and physical decomposition. Having in mind the level of functional, structural (technical) and physical decomposition, a distinction can be made between fixed, partially decomposable, and totally decomposable structures. For example, one building function can be allocated through one independent building system like one façade panel shown in Figure 4.19.

On the other hand the internal arrangement within the system or physical relations between the components and materials of the system can jeopardise the disassembly potential of the system. The composite façade panels in Figure 4.19.a can be dismantled from the main structure. However, further decomposition on the system and component level is not possible because of fixed physical integration between elements of the system (Figure 4.19.b). In the short term this means that this component can be reused as it is, but in the long term, at the moment that it needs adjustments for a new use scenario, it will have to be demolished and landfilled.
Characteristics of material levels, hierarchy and interface design discussed in this chapter indicates the performance of the structure in relation to its deconstruction.



a *b* *c*

Figure 4.19: levels of dependence within the building : for example
a. independent façade system (building level) = separation between façade system and the load bearing structure
b. independent component within façade system (system level) = separation between components within façade system
c.independent element within façade component (component level) = separation between elements within component (Orton 1994)

4.7 OPEN VERSUS CLOSED SYSTEMS = DYNAMIC VERSUS STATIC STRUCTURES

Considering the typology of configurations, basic differences can be found between static and dynamic configurations that correspond to closed and open systems.

4.7.1 Characteristics of conventional closed systems

Conventional building systems are often developed in the form of closed systems, operating independently from other industries, and usually for single building types such as schools, offices, or housing. Such building systems are designed mainly to make use of one material, such as concrete in concrete panel systems, or timber in timber-framed systems. A limited range of parts is designed and produced to simplify the control of all operations, and to ensure total control of the building program.

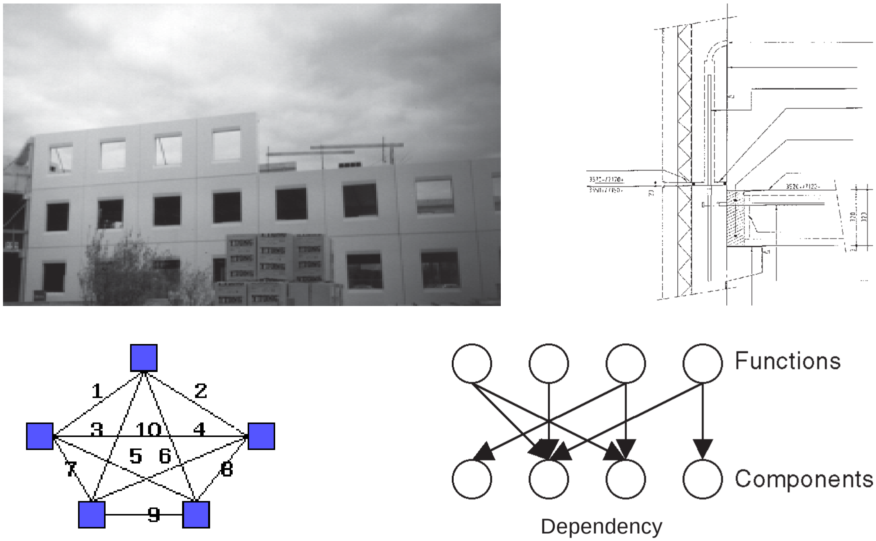


Figure 4.20: Characteristics of conventional closed system building

The main characteristic of most of conventional systems is that they are developed in a form of closed (static) systems, due to the fixed integration of technical systems into functional building systems. This means that materials, elements, components rely on each other in order to provide the desired functionality of the system. They are static by nature and do not correspond to their surroundings.

Closed system building generally uses larger component sizes and often ends up with identical products when combined with mass production.

Although their construction is associated with careful assembly on a construction site, they are usually inflexible during the exploitation and demolition phases. This has to do with integration of different functions and materials into fixed connections, and the lack of accessibility to the components with shorter life cycles (Figure 4.20).

Due to the high level of functional and material integration that form a building system, it is usually impossible to remove components in order to replace or exchange them, without damaging related parts. Therefore, every change within the building can have consequences for the entire building structure. These closed building systems are not suitable for easy transformation, and cannot result in building capable of adapting to the frequent changes of user requirements.
They are mostly characterised by high levels of uniformity, simplifications of building typology and typology of building parts, fixed integration of different functions in one component (Figure 4.20), and a fixed life cycle.

The real meaning of industrialised building however should be understood through the definition that comes from American building practice (R.F.Borg82). ”Systems building” is used to define a method of construction in which use is made of integrated structural, mechanical, electrical, envelop, and partitioning systems. The ultimate goal is integration of planning, designing, manufacturing, site operation management, and financing into a method for cost effective and high quality industrialised buildings.

4.7.2 Characteristics of open systems

Unlike conventional system buildings, that are mostly developed in a form of closed systems, systems building can be seen in a form of an open structure, which is a result of disciplined integration of independent sub-systems. Such structures have the form of an open system that permits continuous change and additions. They can last longer because they can be adapted over time.
The most important aspect of such dynamic systems building is separation and decoupling of sub-assemblies that have different functional and life cycle

expectancies. Such decomposition is a top-down process that should be developed following the criteria that helps us to recognise and decompose the systems from the whole.

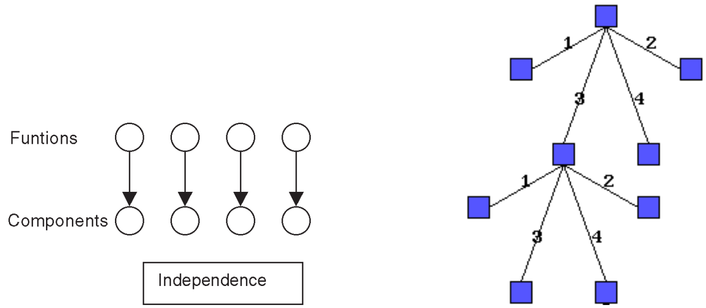


Figure 4.21: characteristics of the open systems building

Therefore, the focus in future developments should be on systematisation of building components into independent subsystems assembled in a hierarchical order suitable for maintenance and replaceability of frequently changed parts. Different sub-assemblies are independent from each other and are connected via base element of the assembly, similar to the composition of computer programs made of independent modules that can be independently upgraded, reconfigured, and added to the existing software.

Such a concept allows for future alterations to external screening, and to internal partitioning. It allows for services to be independent of the fabric, to provide for accessibility, servicing, and alteration. It creates the precondition for reuse and recycling and opens the way for designs of greater diversity and richness (Figure 4.21).

Thus, a building system is not a material and fixed entity; it is a conceptual approach to construction. System thinking requires looking at complex things in such a way that one can comprehend the various parts that make them up - and the relationship between those parts - in terms of the tasks they have to perform.
Systems are by no means neutral but should be seen as specialised ways of allowing for more freedom to create (Ehrenkranz, E.D 1989). System building

requires more specialised, technical experience, and detailed knowledge than conventional ways of building. To take an advantage of the system approach, one has to develop the parts and the relationships between them in such a way that degradation and inefficiency are avoided during all phases of a building's life. (Helmut Schulitz 02)

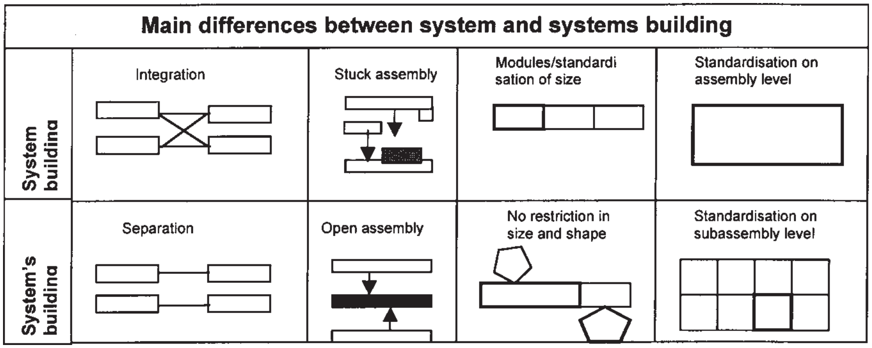


Table 4.3: main difference between open and closed systems

In short, the key differences between open and closed systems can be formulated as follows:

Conventional systems are primarily designed for assembly. Their development was based on wel- known structuring principles for assembly such as: integration of parts, design of stuck assemblies, creation of modules, and standardisation of system levels.

The principles of an open system's design provide variety through greater functional decomposition so that different requirements can be met during a system's life cycle. The main characteristics of such dynamic systems are separation of functions, open assembly, flexible production processes that are not restricted to standard sizes and standardisation on sub-assembly level, which connect mass production to'small size components (Table 4.3). These principles have paved the way for a new type of system development, which shifts the focus from simple static elements to complex components defined by dynamic configurations (Figure 4.22).

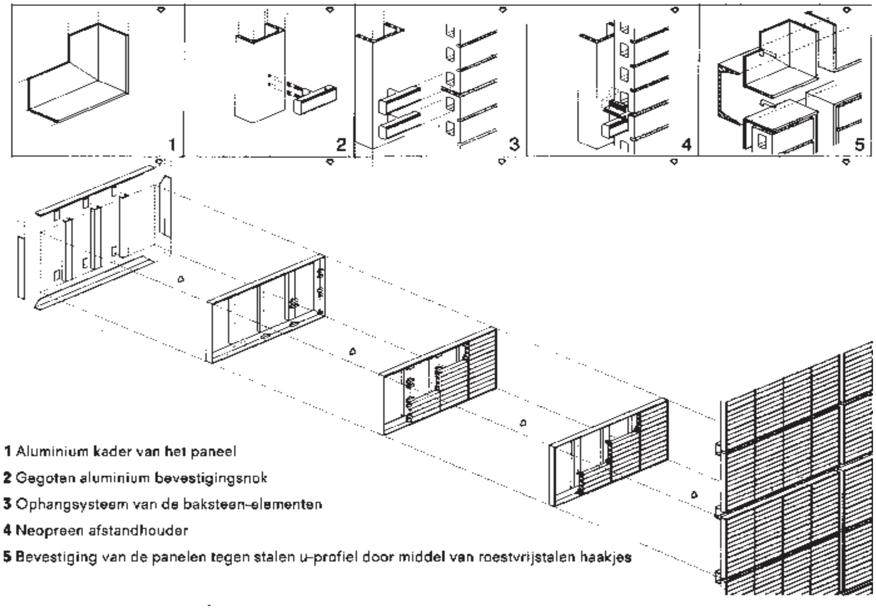


Figure 4.22 Extention of IRCAM Building, façade system designed by Renzo Piano 1987

4.8 DESIGN ASPECTS FOR DESIGN OF OPEN SYSTEMS

In order to design structures that stimulate conscious handling of raw materials and provide high standard of quality of structures through efficient exploitation, the following requirements should be fulfilled:

- Accessibility,
- variation,
- reuse,
- replaceability,
- reconfiguration, and
- recycling

Chapter 5
Design aspects of transformation
Decision making support

Design of transformation is about coordination of loose relations

INTRODUCTION

This chapter argues that design of transformable structures deals not only with the functional, technical, and physical design domains of building composition, but also with the functional, technical, and physical domains of building decomposition.

Relations have been defined between design domains and elements of a configuration (as discussed in Chapter 4). For example, design decisions regarding the functional domain are shaped through specification of material levels. Technical domains relate to decisions regarding this hierarchy, while physical domains deal with the design of interfaces. Although these three domains are separated, they are not independent in the decision-making process.

Chapter 5 proposes that the success of design for transformation with associated disassembly depends on decisions made within design domains of deconstruction.

Design aspects that can facilitate these decisions are defined according to two criteria of building deconstruction: independence, and exchangeability.

It has been emphasised that the transformational capacity of every structure can be assessed based on evaluation of aspects of deconstruction. These aspects are: functional decomposition, systematisation, open hierarchy, base element specification, parallel assembly and open geometry of product edge, demountable connections, and life cycle coordination. These design aspects are also seen as sub-aspects of the three elements of configuration.

Based on their evaluation, it is possible to differentiate between three typologies of configuration, which represent transformable, partially transformable, and nontransformable structures.

5.1 PERFORMANCE CRITERIA FOR TRANSFORMATION

To design transformable building structures, performance criteria upon which design decisions are made, need to be defined. These criteria measure the effect design decisions have on transformation.

The figure 5.01 represents decisions that must be made during the creation of a structure. The first domain is related to specification of the cluster (sub-assembly) in product engineering. These are also called product families. The second domain is related to the position of the element within sub-assemblies, and total assemblies. This aspect deals with the moment of assembly and disassembly that influences relations and hierarchy with the structure. The third domain depends on interfaces between parts.

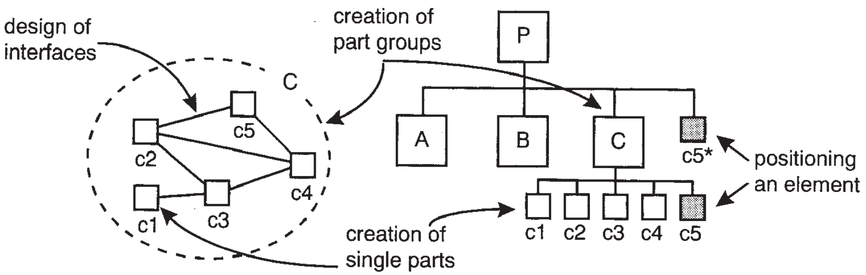


Figure 5.01: decisions in the creation of component structure (M.Tichem 1997)

A structure can be transformed if its elements are defined as independent parts of a building structure, and if their interfaces are designed for exchangeability. One can define *independence* of building components and their *exchangeability* as two key performance criteria for transformable structures.

Independence of parts is determined primarily by functional design domains, which deal with design of material levels and specification of 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.

Although these three main domains of structural decisions concern design of transformable structures, they cannot be made independently of decisions regarding interface geometry, functional integration of parts within sub-assemblies, functionality of intermediaries, materials in connections, and life cycle co-ordination of material and their functions.

This chapter discusses aspects that have an influence on decision-making during design of transformable structures. These aspects are specified as (Figure 5.02):

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.

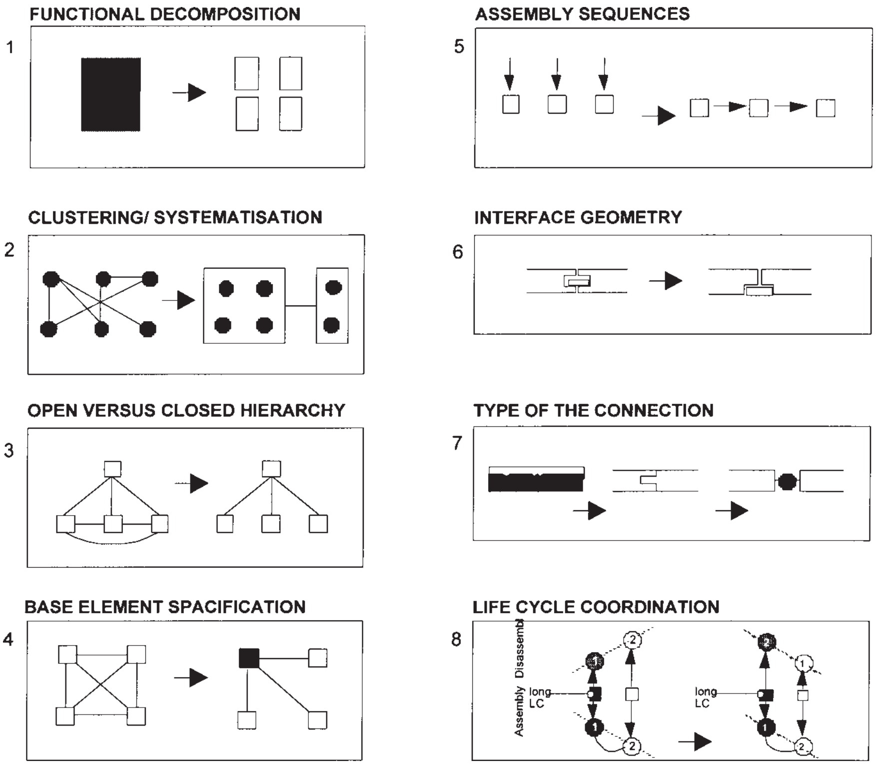


Figure 5.02: Eight design for disassembly aspects of building configuration

Unlike conventional structures in which design deals with functional, technical, and physical composition, the design of transformable structures focuses on functional, technical, and physical decomposition.

The table below presents the dependence between design domains of transformable configuration, performance criteria, and the disassembly aspects of configuration.

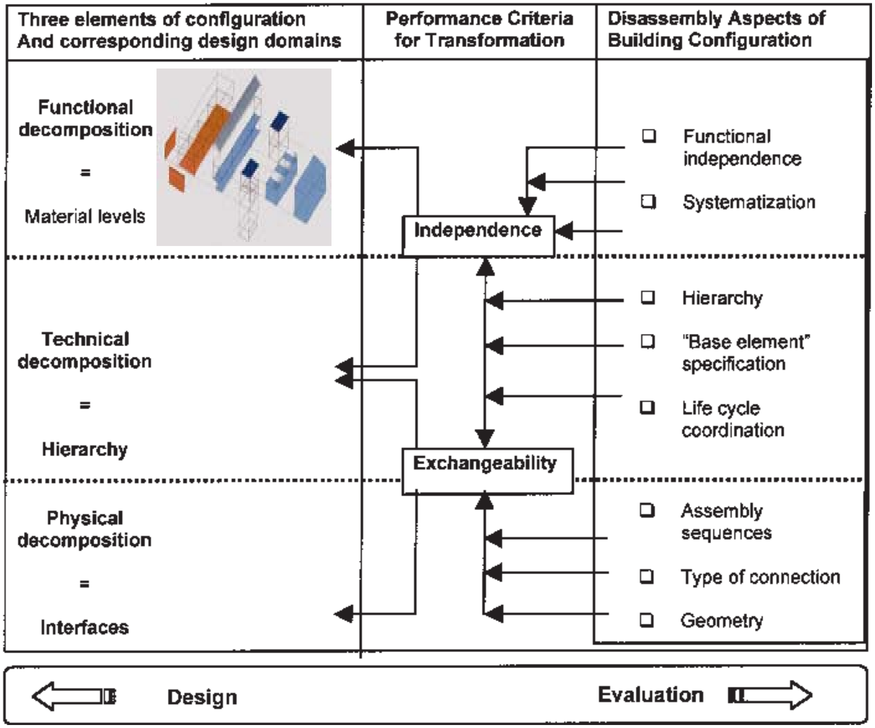


Table 5.1: Relation between disassembly aspects and design domains

Although decision-making groups that consider configuration design can be distinguished, they cannot be separated because of dependencies that exist between decision-making groups (see table 5.1).
Later sections treat design domains and their mutual dependencies within the decision-making process of the design of transformable structures.

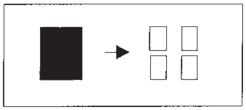
5.2 FUNCTIONAL DECOMPOSITION

Functional decomposition is one of the first domains that designers face when designing flexible structures. Decisions whether two or more functions are integrated into one building product or whether separate products are carriers of separate functions provide the first indication about a building's transformability. These decisions are made during the specification of material levels. Whether two functions are really separated also depends on relations between elements. These depend on their geometry and interfaces, and on the creation of sub-assemblies.

Main aspects of functional decomposition are:

- functional independence, and
- systematisation of elements.

5.2.1 Functional independence



Level of separation between different functions within one configuration, and the level of autonomy of independent functions, determines this aspect.

Functional separation

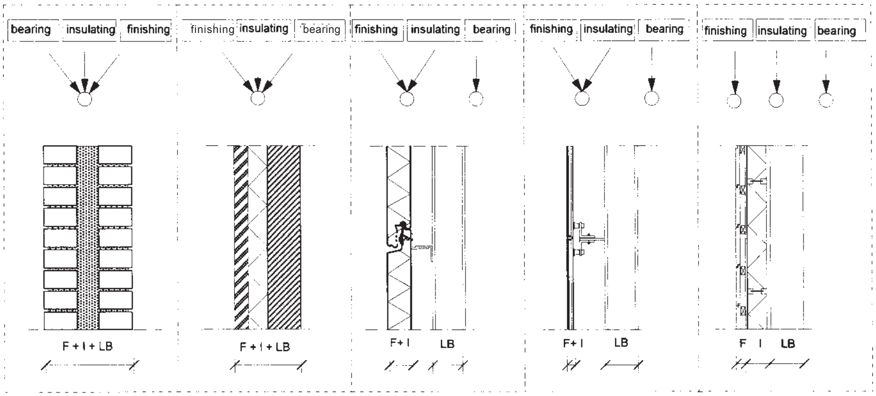
Three scenarios can be distinguished that determine the level of functional separation: integration, incorporation, and separation (Figure 5.03 and 5.05). Design for disassembly favours total separation between different functions, on all building levels.

Figure 5.03: Separation of functions versus integration of functions

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 behaviours, 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 decomposition plays an important role in life cycle co-ordination.

Traditionally, external walls due to their mass and thickness accommodated various functions such as, carrying of vertical and horizontal loads, insulating, finishing, and providing light.
Because of their heavy, composite structure, such walls were seen as static and fixed elements of a building. Today, such walls have gained dynamic aspects, since they must enclose different kinds of activities that change frequently. There may be different requirements for appearance, size, and position of openings. Sometimes, even their position is an issue. Therefore, the need emerges to dismantle all functions kept within composite wall structures and allocate them instead to independent components. Therefore, change or substitution of one function does not influence the integrity of others. Figure 5.04 illustrates five types of walls and their functional composition.



F - Facade
LB - Loadbearing structure
I - Insulation

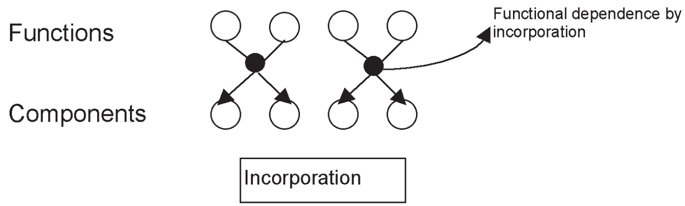
Figure 5.04: Integration of functions within an exterior wall system

Functional autonomy

Incorporation provides a partial dependency between independent functions by planned or unplanned interpenetration of components having different functions. (Figure 5.05)

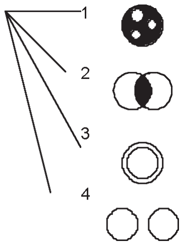
This means that relocation or resizing of components that have one function influences the integrity of other components that have other functions.

Figure 5.05: Functional dependency by incorporation



Incorporation of independent functions, result in the following scenarios:Total integration , planned interpenetration, unplanned interpenetration, total separation. (Figure 5.06)

Figure 5.06: four scenarios of functional incorporation which define the level of functional autonomy



1) Total integration / unplanned integration
2) Planned interpenetration
3) Unplanned interpenetration
4) Total separation /independence

For example, integration between structure and services (Figure 5.07):

Scenario 1:

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.

Scenario 2:

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

Scenario 3:

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

Scenario 4:

total separation or zoning.

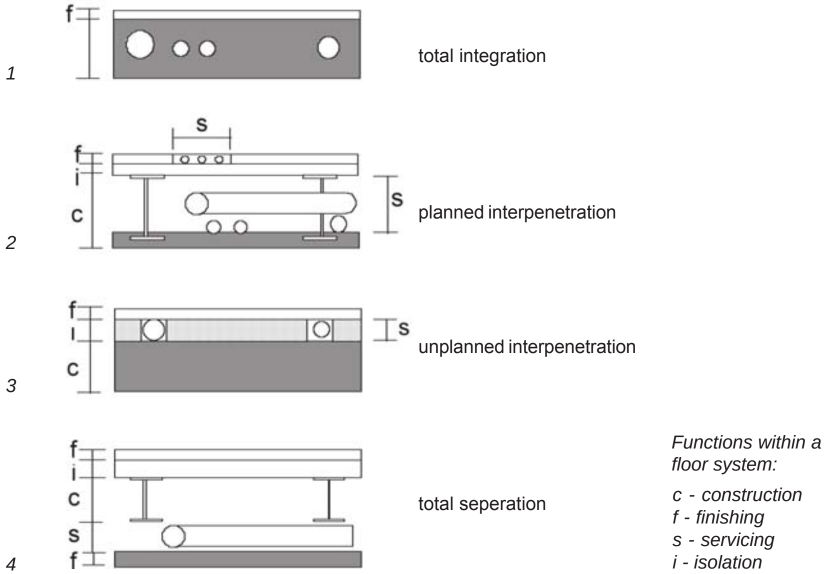
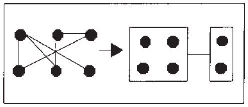


Figure 5.07: Levels of functional autonomy within a floor

Functional incorporation can also be shown using examples of façades. Often, relocation or resizing of façade openings has consequences on load bearing elements, or on the finishing of a façade. Portions of a brick façade as well as its inner wall may need to be demolished .

5.2.2 Systematisation



This section discusses the systematisation of single parts into sub-assemblies. Aspects of systematisation deal with decisions about creation of clusters according to their life cycle performance requirements, and on the level of integration of material levels.

Specification of sub-assemblies

A sub-assembly is a cluster of parts that acts as an independent building section in production, exploitation, and assembly / disassembly. The greater the number of building parts integrated into one component, the fewer are the physical connections needed on site (Figure 5.08). In this way assembly and disassembly processes can occur in three stages: on site, in the work place, and in the factory. Such a strategy is the first step towards greater control of efficiency of materials use.

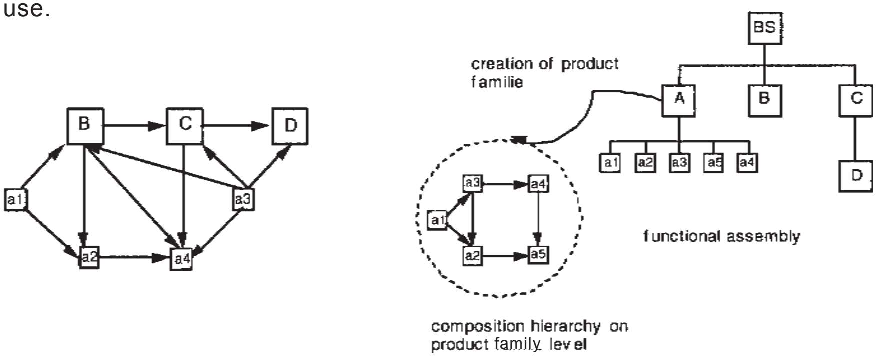


Figure 5.08: Clustering of products into product families (the term used in product industries) can reduce the number of on-site assembly/disassembly operations. This leads to faster, less labour intensive and thus more feasible on-site transformations.

Systematisation and modulation of building parts into a subsystem also provide structures, whose performances during operation and maintenance phases, can be controlled.

The design team defines sub-assemblies based on required performance, production flexibility, system design, and geometrical or mechanical criteria.

A building can have a number of levels of systematisation. However, four types of clustering can be distinguished (figure 5.09):

1. clustering on the system levels,
2. clustering on the component levels,
3. clustering on system, component, element and material levels,
4. no clustering.

The system is the most representative collection of parts that represent major building functions. The system is the highest material level of composition and has a number sub-levels, such as: sub-systems / components, elements, and materials. As discussed in Chapter 1, the number of disassembly options can be an obstacle for transformation. If too many 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 replaced for reuse/reconfiguration, and secondly in the factory, where lower levels subassemblies, such as sub-components and elements, are disassembled and replaced for reuse/ reconfiguration/recycling.

Figure 5.09 shows four types of building configuration distinguished by the number of on-site assembly/disassembly operations. The problem of coordination between different components and their assembly/disassembly operations grows along this systematization from 1 to 4.

For example, a façade system can be structured following the pattern of functional decomposition, into sub-functions such as: enclosing, finishing, isolating, water protecting, and load bearing. Sub-functions can be allocated through independent elements arranged into components, to form a particular façade system (Figure 5.10 right). These components are materialisations of sub-functions. In this way, the façade system is composed of components that can have different use and technical life cycles. This makes the façade system flexible, because it can be easily modified, according to new requirements regarding light, insulation, position of openings, etc. At the same time, components can be reused in other situations, reconfigured or recycled. Development of such systems takes into account both short-term strategies related to adaptation for future use, and a long-term strategy related to the most beneficial end-of-life building component scenario. Houwever, if there is no clustering with respect to systems sub-functions than most of systems sub-functions are integrated into one composite component. Figure 5.10 left illustrates such a system, where the load-bearing functions, light openings, and subdivision of openings are combined into one material level. This system has been developed for construction of a number of housing towers in Hong Kong. Such a system structuring lacks transformational capacity and cannot be adapted to different use requirements. At the end of a system's service life, the only end-of-life scenario is demolition and down-cycling of material.

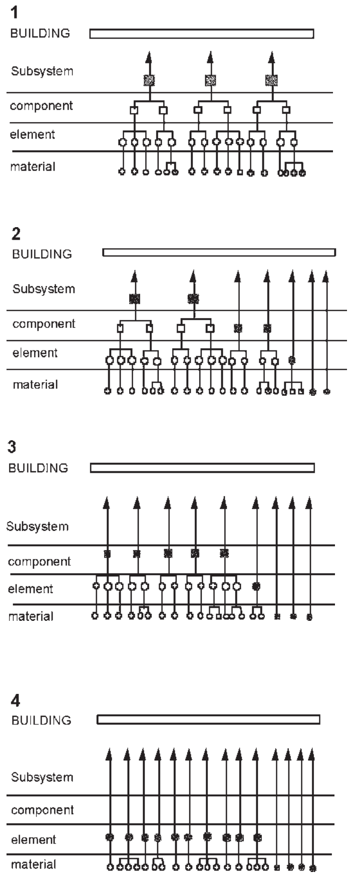


Figure 5.09: Four types of building configuration distinguished by the number of on-site assembly/disassembly operations.

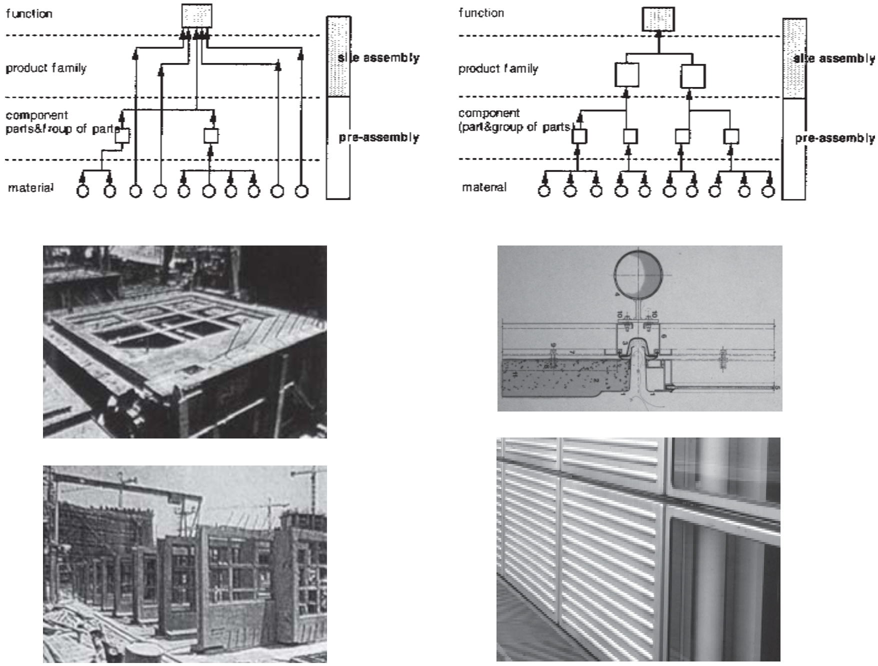


Figure 5.10: Left, assembly procedures illustrate no clustering of materials during technical composition of the system. Right, assembly procedures illustrate clustering on the component level of technical composition of the system.Left close system configuration, right open system configuration

Systematisation of building elements and materials into clusters is directly related to the functionality of the cluster, assembly sequences, and maintenance related to the technical life cycles of components. Functionality of a module determines which materials and elements form the cluster, while use and technical life cycles determine the sequential order, preferable type of hierarchy within the cluster, and type of relations with other clusters.

The more elements are systematised into independent assemblies according to their functions, the easier is the life cycle and functional coordination between them. Therefore, assembly and disassembly sequences are easier to plan.
Static configurations correspond to the building structure represented by the maximal integration of all material levels resulting in one building level.

This is the case when materials are used on site. Totally decomposable structures are dry assemblies, in which material levels of technical composition, and parts within material levels of technical composition can be separated.

5.2.3 Decision-making regarding material levels in the design domain of functional decomposition

Decision-making during design of sub-assemblies deals with questions of functionality, fast assembly, and separation of fast cycling, and slow cycling elements.

This means that decisions that influence the design of clusters are: geometry, hierarchy, and type of relations between clusters, and within clusters. (Figure 5.11)

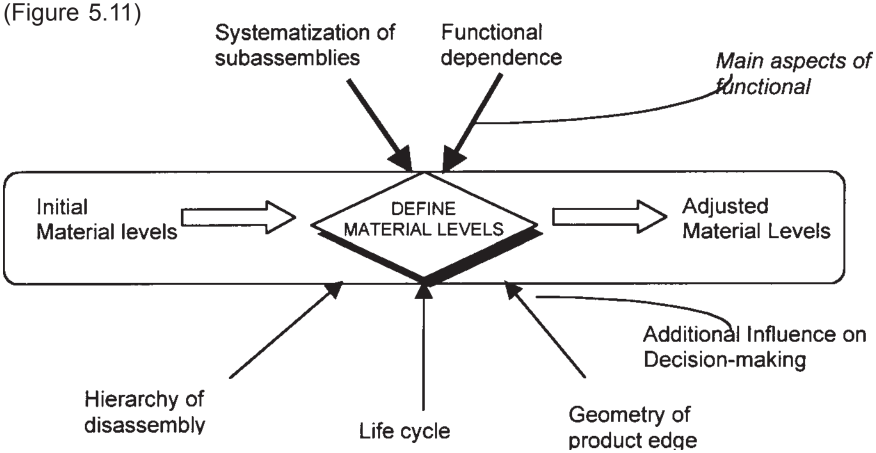


Figure 5.11: Design considerations regarding functional decomposition. Valid design decisions with respect to functional decomposition cannot be made during the conceptual design phase, which deals predominantly with the functionality of the assembly, because additional analysis is needed. Therefore, the design process recognizes that conditional discussions will be made definitive at the moment all necessary aspects have been considered. This is the reason why cyclic (not linear) decision making processes are more representative for the whole DfD process.

Therefore, functional independence is influenced not only by separation of functions, but also by design decisions regarding the ordering of elements (technical de composition), and interfaces between elements (physical decomposition) with respect to disassembly.

Although systematisation can be defined as part of the functional decomposition domain, decisions about systematisation cannot be made independently of the technical and physical domains of the structure.

This dependency between design aspects is illustrated in the figure above.

5.3 TECHNICAL DECOMPOSITION

This section discusses decision-making regarding technical decomposition that defines the order within a configuration.
This aspect is predominantly defined by the:

- relational pattern,
- type and position of relations, and the
- base element specification.

Differences can be seen between structures that do not have clear order and hierarchy (structures simply represented by the sum of their elements and unselective relations), and structures with a clear order within whose functions and elements can be identified and whose assembly hierarchies correspond to the replacement schedules of change-sensitive elements (Figure 5.12).

Relations between different components and dependencies between different functional groups within a system.

The level of dependencies between components because of assembly sequences.

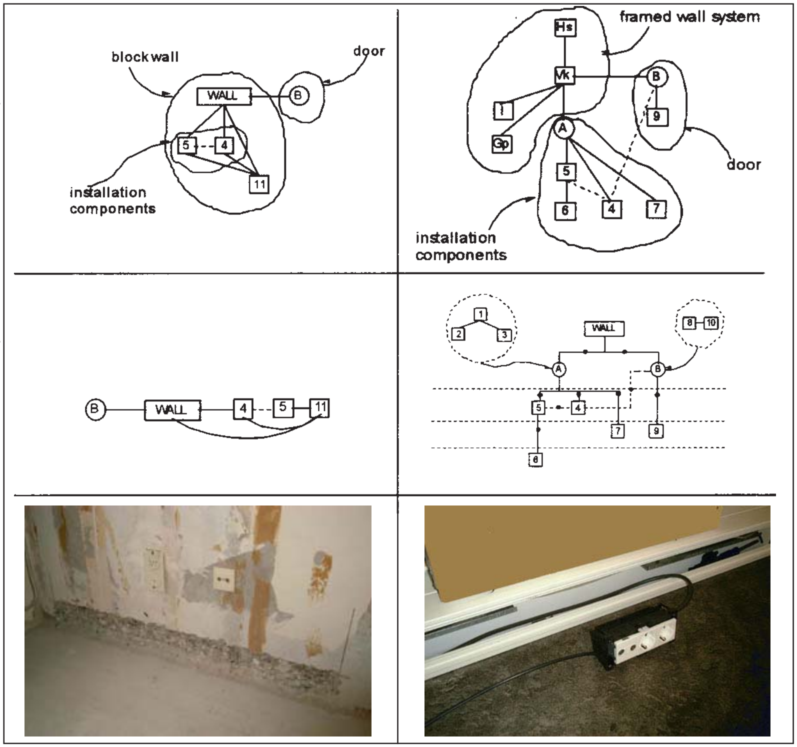
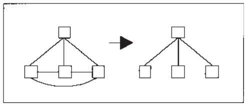


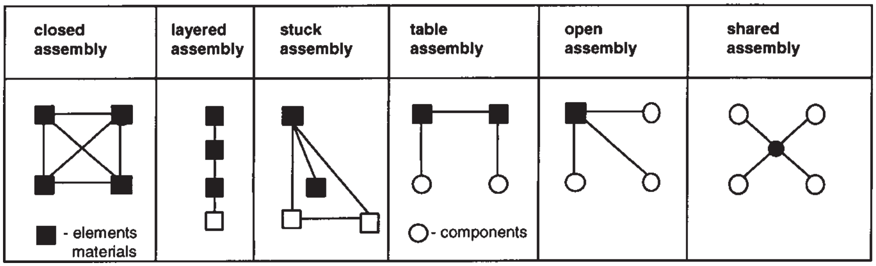
Figure 5.12: Technical composition/ decomposition of two wall systems Left traditional wall with inserted electrical components (fixed integration of all elements of the system) Right flexible wall with separated electrical components (separation between different functional groups)

It is possible to recognise relational patterns within structures that illustrate this order. The position of a relation informs us about dependency between functional groups. The third aspect, which plays a role in independence and exchangeability of elements, is the base element. The hierarchy within the structure defines the order, which represents the load path through the building. This means that a hierarchy also implies a dependency, based on gravity. Loads can be transferred through the building directly from one element to another. In this way all elements become dependent on each other. Independence within a structure can be achieved by introducing a third part, which acts as a base element and takes over the load bearing function. This principle can also be applied when providing integrity to other functions in the building. The base element is simply an intermediary between different functions and surrounding elements.

5.3.1 Relational patterns

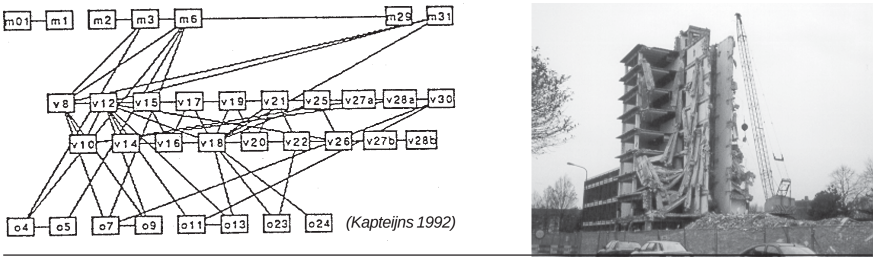


Traditional buildings were characterised by complex relational diagrams, which represented maximal integration of all building elements into one dependent structure.
In such an environment, substitution of one element could have considerable consequences on related parts at their connections.
The most 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, 6. shared assembly (Figure 5.13).



5.13: Classification of assemblies according to the type of relational patterns

Buildings whose materials are not systematised and clustered into independent units, represent static assemblies. Static configurations represent patterns that result in closed, layered, or stuck assemblies. The table - assembly characterises partially open systems. Within open hierarchies, building parts are kept independent from one another by only creating dependent relations to elements within an assembly. In this research, these are called frames or base elements. Shared assemblies are ones in which connections are designed as base parts for the total assembly. This provides a great level of freedom when defining the form and size of connected elements. Relational patterns also define the type of building configuration. Figure 5.14 shows three distinguished types of configuration.

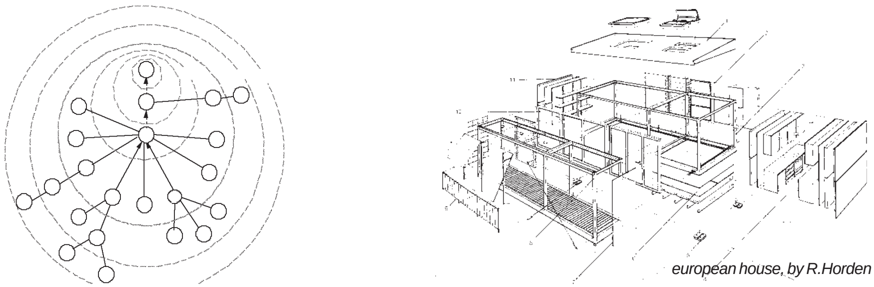


(Kapteijns 1992)

5.14 a: relational pattern representing a closed assembly

(Kapteijns 1992)

5.14 b: relational pattern representing development towards a table - assembly



european house, by R.Horden

5.14 c: relational pattern representing an open assembly

5.14: three types of configurations could be distinguished based on their hierarchical systems. Static, dynamic and partly dynamic configurations refer to closed (figure on top), open (figure bellow) partly open hierarchical systems (figure middle).

Position of relations

Relations within sub-assembly versus relations between sub-assemblies

A building and each if its parts, must fulfil specific functions. The relational diagram can represent relations between different family groups, where each column represents one family group. Configurations that have vertically-oriented relational diagrams can be seen as dynamic, while horizontally oriented ones can be seen as static.

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

All elements can be systematised in columns that correspond to building functions and hierarchy of assembly. Vertical relations represent relations within one functional group, while horizontal relations represent relations between different functional groups. Ideally, different functional groups should not have direct relations. This makes replaceability and modifications of different requirements easier. A relational diagram that represents relations between different functional groups of building, illustrates the functional dependency or independence of a building configuration. That means that horizontal relations are not desirable in configurations suitable for modification and replaceability of constituent parts. Configurations that have vertically oriented relational diagrams, are called dynamic. The only horizontal relations that can exist within dynamic configurations are ones between base elements of a sub-assembly, and base elements of the total assembly. These elements will be dismantled last. Horizontally-oriented relations represent static configurations because horizontal lines indicate a dependency between elements having different functions. If relations between different functional groups are positioned higher in an assembly hierarchy, a greater number of elements are needed to be disassembled in order to reach that particular relation.

Figure 5.15 represents three types of separation walls. Figure 5.15 A is a traditional wall with inserted electrical installations; Figure 5.15 B is a traditional wall with separate zones for cables in the wall and doorframe. Figure 5.15 is a metal click wall with zone for cables in the floor and in the wall.

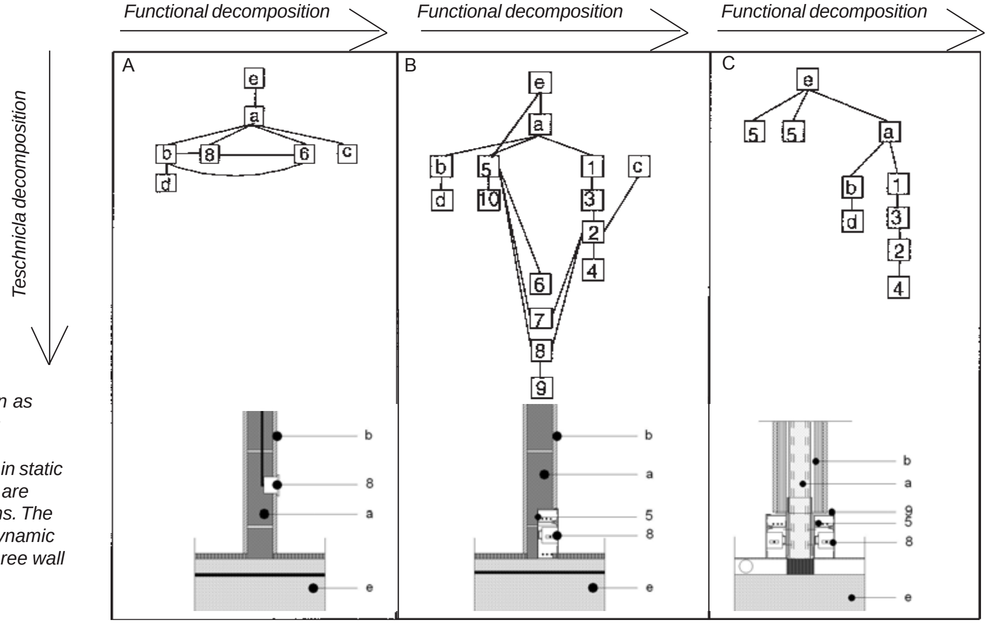
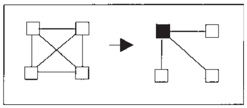


Figure 5.15: type of configuration as result of the position of relations between the functional groups. Horizontal relations are common in static configurations, vertical relations are common in dynamic configurations. The figure represents static, partly dynamic and dynamic configurations of three wall systems.

Horizontal relations in Figure 5.15 A illustrate dependencies between the separation wall, electrical installation, and finishing. If one element needs to be replaced, all surrounding elements would be damaged. Figure 5.15 B and C illustrate more vertical relational diagram that represents a partially open and open hierarchy of wall systems, which have a greater transformational capacity.

5.3.3 Base element specification



A building product is a carrier of specific functions or sub-functions. Each assembled product represents a cluster of elements that are carriers of sub-functions. To provide independence of elements within one cluster from the elements within other cluster, each cluster should define its base element, which integrates all surrounding elements of that cluster. Such elements share their functions on two levels in buildings: (i) to connect elements within independent assemblies, and (ii) perform as an intermediary with other clusters.

Figure 5.16 shows four principles of defining the façade and the role that specification of a base element can have on decomposition of a façade element. Principle 1 in Figure 5.16 is based on the assumption that building parts are assembled on site. In this principle, elements, which according to their functionality belong to the functional assembly of the façade (f1), have direct relations with other functional assemblies (load-bearing construction) (f2). 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 façade assembly, and at the same time has a load bearing function in the building. This makes the construction process simpler, however, change of one façade panel would have consequences for the stability of the total structure.

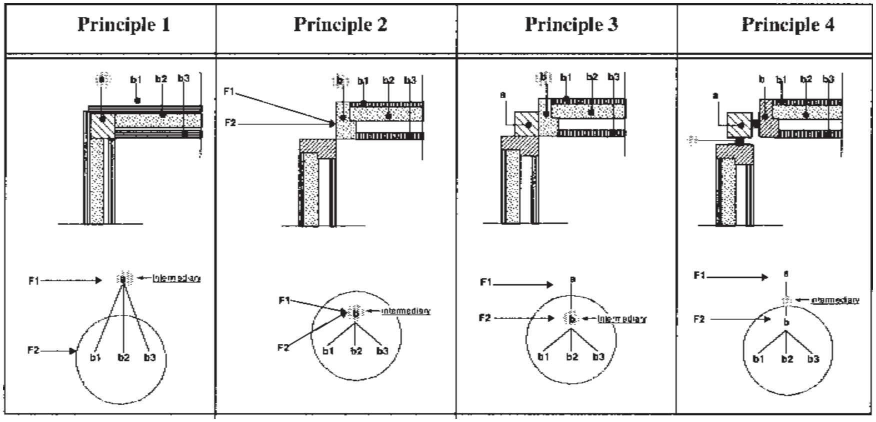


Figure 5.16: Four principles of base element specification

Principle 3 shows an independent assembly of two independent functions (f1, f2). Elements assembled as façade (b, b1, b2, b3) are clustered into one component, where the wooden frame (b) is chosen as the base element. The load-bearing function (a) is taken out and defined as an independent assembly. In this case, the load bearing elements act as a frame for the whole building and the wooden frame b is the base for the façade assembly. This serves as an intermediary between the load bearing assembly and independent elements of the façade.

In Principle 4, a connection has function of intermediary between two independent assemblies. In this case, the replaceability of a façade element (b, b1, b2, b3) would not have an effect on other assemblies.

5.3.4 Decision support regarding technical decomposition

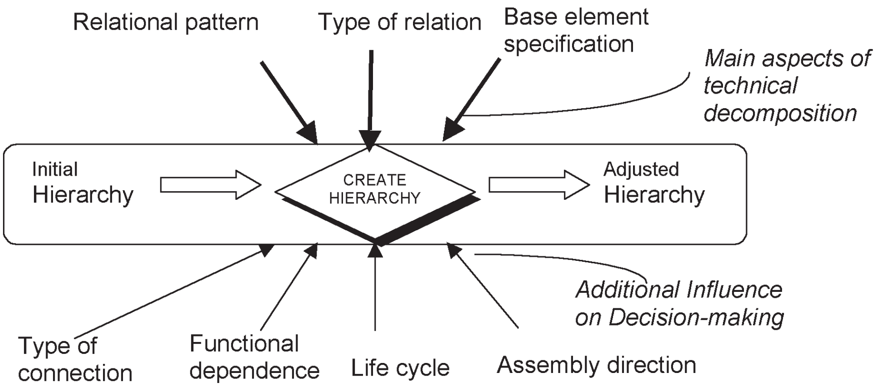


Figure 5.17: Design considerations regarding technical decomposition

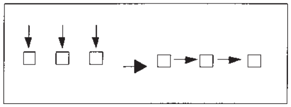
5.4 PHYSICAL DECOMPOSITION

This section discusses the aspect of design of connections between components that support exchangeability of components, and accordingly, contribute to the increased disassembly and transformation potential of structures.

Design aspects involve physical decomposition:

- geometry of component edges,
- assembly sequences,
- type of connections, and
- life cycle coordination.

5.4.1 Geometry of product edges



Disassembly sequences can be affected by changing the geometry of product boundaries. This aspect of the product feature is closely related to the interface design and specification of the connection type. Figure 5.18 illustrates six situations that define the suitability of geometry for disassembly of components. Distinction 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.

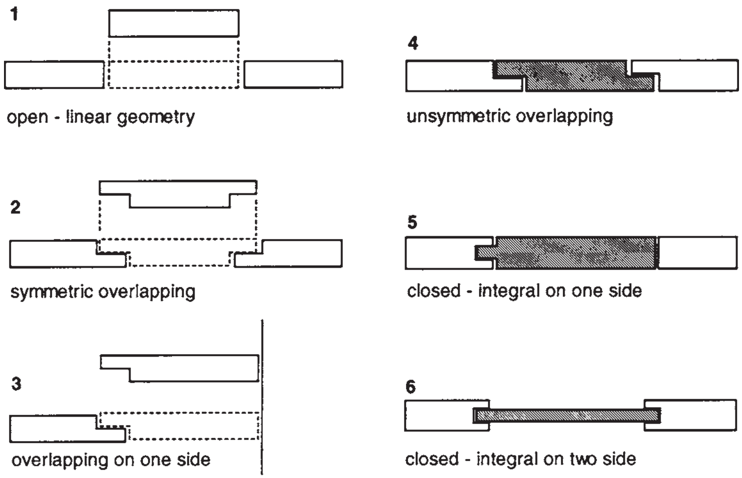


Figure 5.18: Six types of geometry of product edge that influence the level of physical decomposition and transformation level of configuration

Figure 5.19 left illustrates a standard detail often used in housing projects in the Netherlands. In this case, disassembly of the window is not possible.
This is improved by changing the geometry of the connection, as shown in Figure 5.19 right.

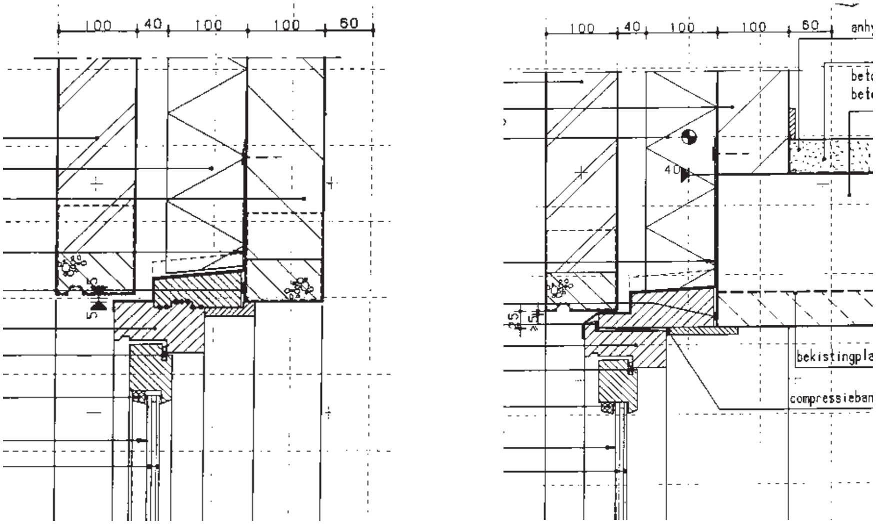
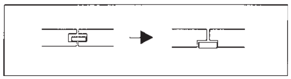


Figure 5.19: Left, closed - integral geometry
Right, overlapping geometry

5.4.2 Assembly sequences



The life cycle of assembled materials, type of materials, geometry of product edge, and type of connections influence assembly sequences.
The key factor for flexible building structures is their ability to be dismantled. This means that structures should have an ability to be taken apart with a minimum of destruction or waste. Sequences in assembly create dependencies between building elements, by locking elements together. The way we assemble a building sets the mirror image of the building during its transformational phase.
The following aspects are important when designing for assembly: 1. Type of products that meet requirements. All building elements can be divided into three categories: raw material (M), half made product (V), and a fully pre-made product (O).

Assembly direction

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

A parallel assembly sequence can speed up a building process. Sequential assembly sequences create dependencies between assembled elements, and makes substitution more complicated.

Five assembly relations can be defined based on the above-mentioned principles. Arrows in the figures 1 to 5, represent assembly direction (Figure 5.20).

1. Parallel assembly. Disassembly depends on the type of connections between elements.
2. Sequential assembly. Each element in this assembly is fixed by a newly assembled element. In this way a linear dependency is established, which is proportional to the number of assembled components.
3. Each element in this assembly has the same dependency as in number 2.
4. This assembly scheme is a combination of 1 and 2. Transformational aspects of such a scheme are related to the:
    - function of the elements assembled in the first three sequences, and the
    - life cycle of elements assembled in the first three sequences, and type of connections.
5. This is an assembly where one element functions as the base element for all others. The key transformational aspect here is the type of connection between distinct elements.

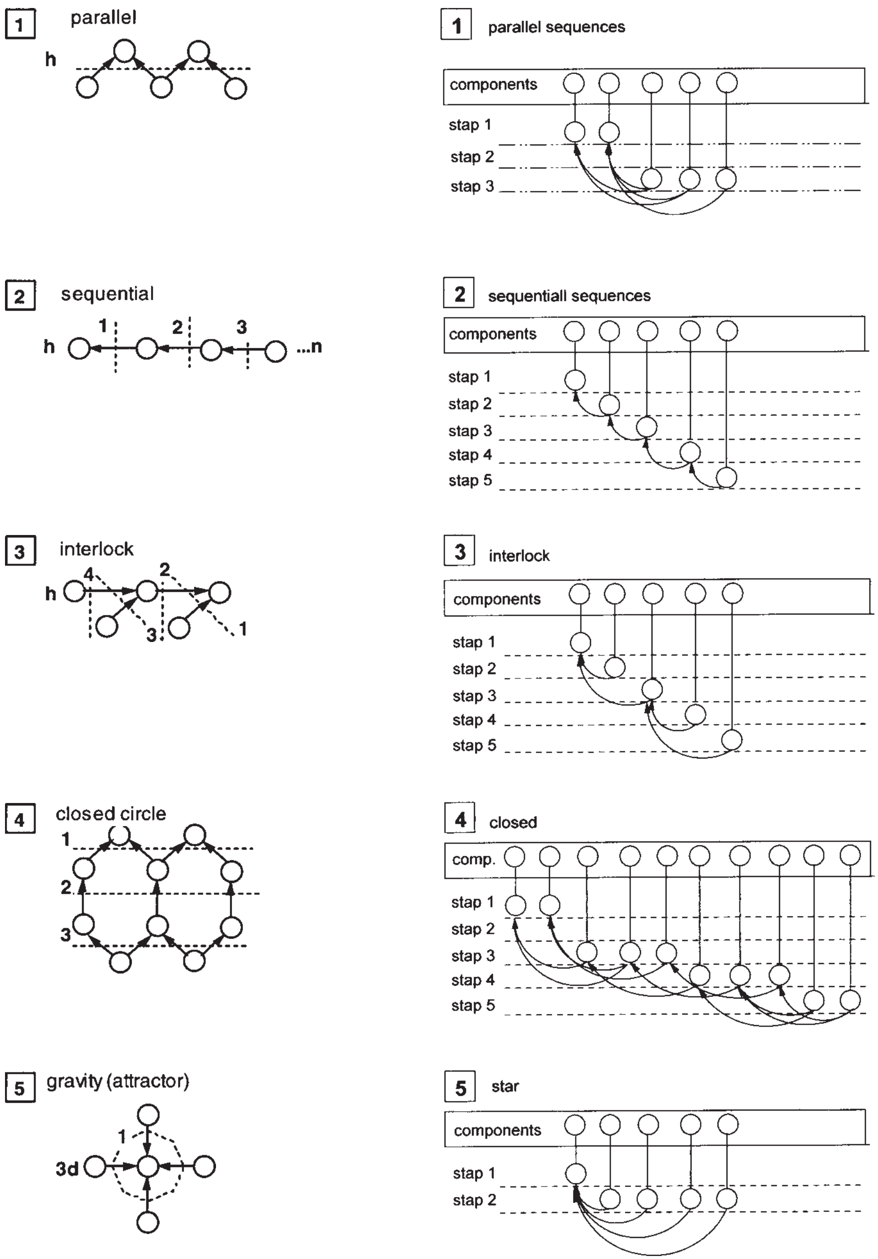
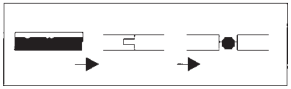


Figure 5.20: Five assembly relations play a role in typology of the configurations. Distinction is based on the assembly direction.

5.4.3 Connections



Design of building connections is the last aspect of design for disassembly. 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. This complicates disassembly.

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 on site with chemical material. Assembly of such components is labour intensive. They can be welded connections between metal plates, between beams and columns,

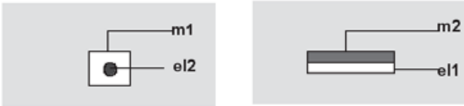
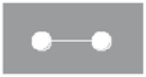
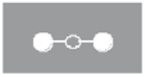
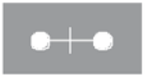
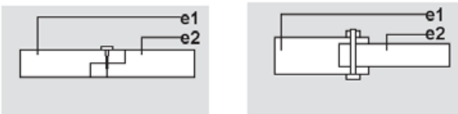
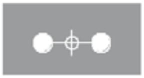
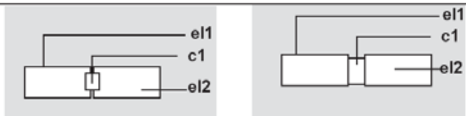
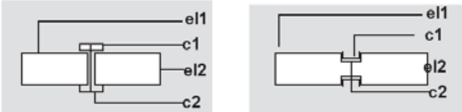
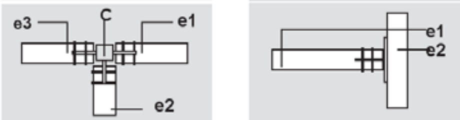
fixed		type of connection	graphic representation	dependence in assembly
		I **Direct chemical connection** two elements are permanently fixed (no reuse, no recycling)		m1 — el2
		II **direct connections between two pre-made components** two elements are dependent in assembly/ disassembly (no component reuse)		el1 → el2
		III **indirect connection with third chemical material** two elements are connected permanently with third material (no reuse, no recycling)		el1 — 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		c1 → el1, c1 → el2
		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 → c1 → el2
		VI **indirect connection via independent third component** there is dependence in assembly/ disassembly but all elements could be reused or recycled		el1 → c1 ← el2, el1 → c2 ← el2
flexible		VII **indirect with additional fixing device** with change of one element another stays untouched all elements could be reused or recycled		e3 → C ← e1, e2 → C

Figure 5.21: Seven principles of connections ranged from fixed to flexible connections.

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.

Type of connections is determined by type of material in connection, does it has accessory, type of accessory and position of accessory.

Four basic displacements that together make all transformations in the structure are: elimination, addition, relocation, and substitution. The structure of a building or its parts can be transformed by elimination of an element. It can also be transformed by addition of an element, the element can simply change its position in the building, or the element can be substituted with another one. Key technical problems are the capability of an interface to provide decomposition, re-composition, incorporation, and plugging-in.

Therefore, 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.

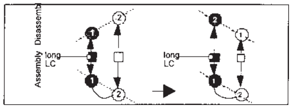
These conditions should be applied to all levels in a building. In this way all building systems become demountable, each component and element is replaceable, and all materials are recyclable.

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.

According to the above-specified characteristics, connections can be grouped in a hierarchical order from fixed to flexible. Figure 5.21 gives a hierarchical overview of the most common solutions. Principle 7 (accessory connection) provides technical solutions to all four transformational criteria. Principle 1 represents the connection between two raw materials that 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 that represents connection between two elements with a chemical connection, and Principle 4 where a partial lap connection with additional fixing accessory creates the precondition for decomposition and replaceability. Finally, principles 5, 6, and 7 represent dry connections, where the position of accessories and their fixings determine the actual disassembly potential.

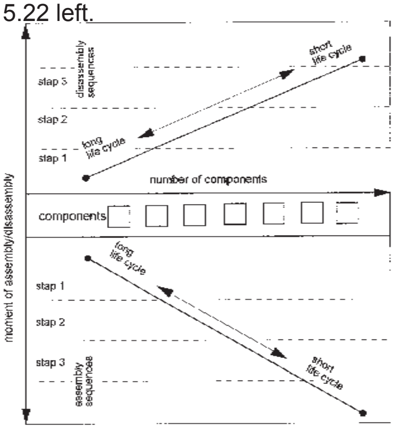
5.4.4 Life cycle co-ordination of materials and its functions in assembly



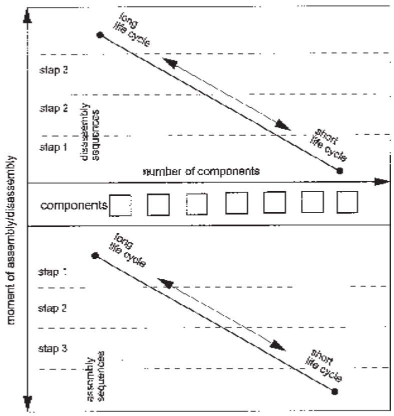
One aspect of life cycle coordination in assembly deals with integration of materials with respect to their life cycle. Building materials have life cycles ranging from 5-75 years, yet frequently, assembly sequences of materials do not consider this. Materials with shorter life cycle are often assembled 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. By later assembly, less disassembly dependency is created as well.

The level of life cycle coordination can be illustrated by a assembly/disassembly diagram, which is illustrated in Figures 5.22 left and right. In general, difference can be made between symmetric and parallel diagram. Symmetric diagram illustrates the assembly, wherein the elements, which have long life cycle, are assembled first and disassembled first. This means that all other elements have to be disassembled as well. Such a principle has been presented in the Figure 5.22 left.



Symmetric assembly/disassembly diagram which indicates lack of life cycle coordination for disassembly.



Parallel assembly/disassembly diagram which indicates life cycle coordination which supports concept of disassembly.

Figure 5.22: diagram show the relation between durability of materials and moment of their assembly/disassembly

If, however, the intermediary within this assembly would have the same or longer life cycle than the other elements of the assembly, the whole assembly becomes more dynamic and transformable. The change of the life cycle of intermediary transforms a symmetric assembly/disassembly diagram into a parallel one. Contrary to the symmetric diagram, a parallel assembly/disassembly diagram illustrates the assembly wherein the elements which have short life cycle are assembled last and disassembled first as is the case in the Figure 5.22 right.

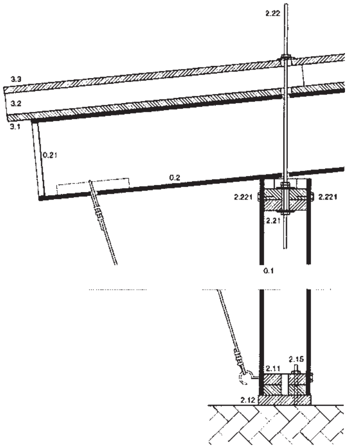
Two life cycle co-ordinations are significant for transformable structures:

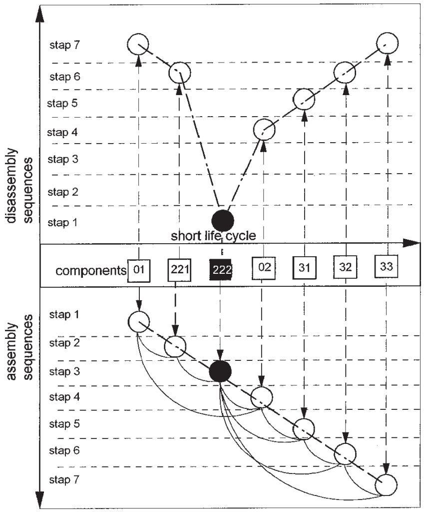
- assembly of materials, which have different life cycles, and
- assembly of materials, whose functions have different life cycles.

The table below illustrates the life cycle coordination between materials, and their functions, in a pavilion building. The disproportion between use life cycle of an element and its technical life cycle is embedded in intermediary component 222. However, the hierarchical diagram in Figure 5.23 shows that component 222, which also has the shortest technical life cycle, has relations with more than three elements of the configuration. This means that the replace-ability schedule of base element can disturb the integrity of the whole configuration. This can be seen in the assembly/disassembly diagram in figure 5.23.

use life cycle		technical life cycle												
		0.1	0.11	0.2	222	221	211	1.3	1.4	3.1	3.2	3.21	3.22	3.23
Load baring constuctio	10	15	5	15										
enclosing verrical	10					15	15	5	10					
enclosing horizontal	10									3	5	25	5	5
intermidier	10				5									

It illustrates the number of disassembly steps which must be done to replace component 222, and its dependency in assembly. Integrity of the whole structure is destroyed after five years, because of lack of life cycle coordination of components in the configuration.





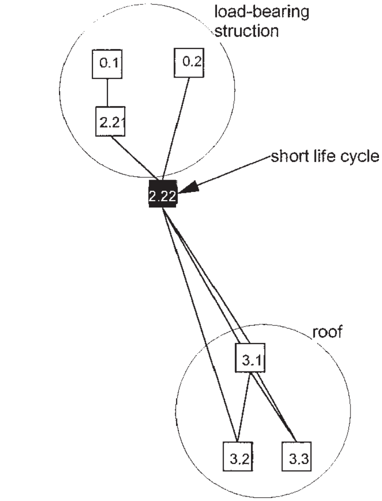
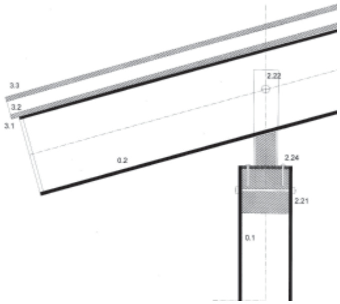
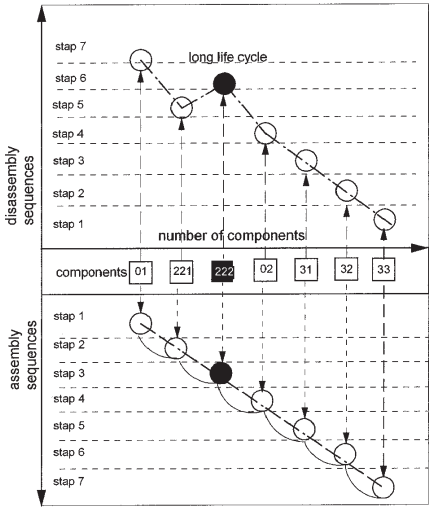


Figure 5.23: building configuration within which an element with short life cycle has function of base element. At the moment of replacement of base element for the reason of maintenance most of the elements within configuration will be disturbed.





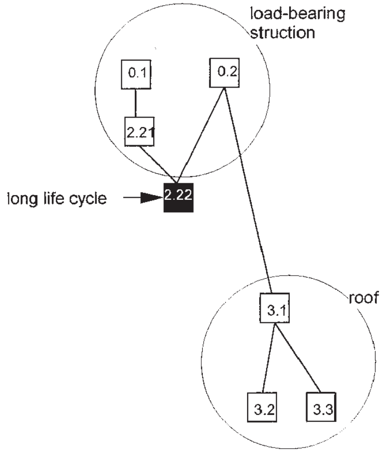


Figure 5.24: The alternative to the solution in figure 5.23. The material that is used for the materialisation of the base element has longest life cycle within configuration.

An alternative to assembly dependency illustrated above, can be found in the introduction of an intermediary, whose life cycle is at least as long as the life cycle of connected elements. (see table below)

use life cycle		technical life cycle												
		0.1	0.11	0.2	222	221	211	1.3	1.4	3.1	3.2	3.21	3.22	3.23
Load baring constuctio	10	15	5	15										
enclosing verrical	10					15	15	5	10					
enclosing horizontal	10									3	5	25	5	5
intermidier	10				50									

Figure 5.24 shows alternative to the solution in Figure 5.23. The material used for the materialization of the base element has the longest life cycle within the configurations. Such optimisation is directly related to functional decomposition of the load bearing structure, as well as the functional and physical relations between the roof assembly and the load-bearing structure's assembly. Thus, consideration of the life cycle coordination cannot be left to later design phases since its optimisation can affect the early design concept.

5.4.5 Decision support regarding physical decomposition

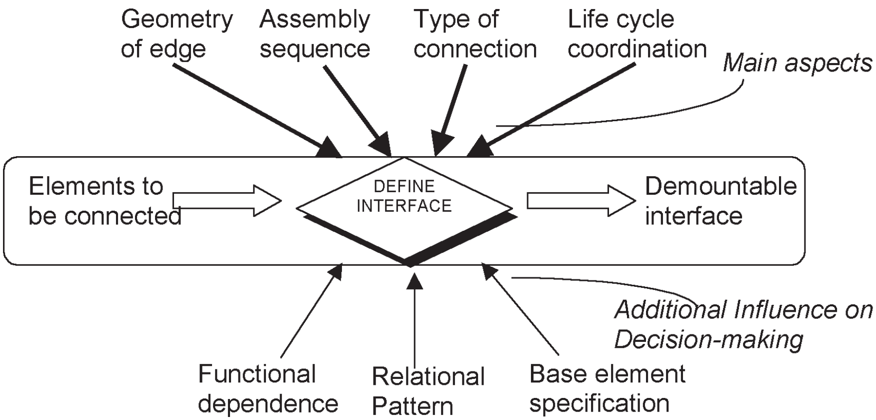


Figure 5.25: Design considerations regarding the physical decomposition

5.5 TYPOLOGY OF TRANSFORMABLE CONFIGURATIONS

Whether components that have fast cycling rate are independent and exchangeable, depends on attention given to design aspects for disassembly. These aspects indicate the typology of a designed configuration. As mentioned in Chapter 4, all configurations can be judged according to criteria ranging from static to dynamic (See Figure 5.26).

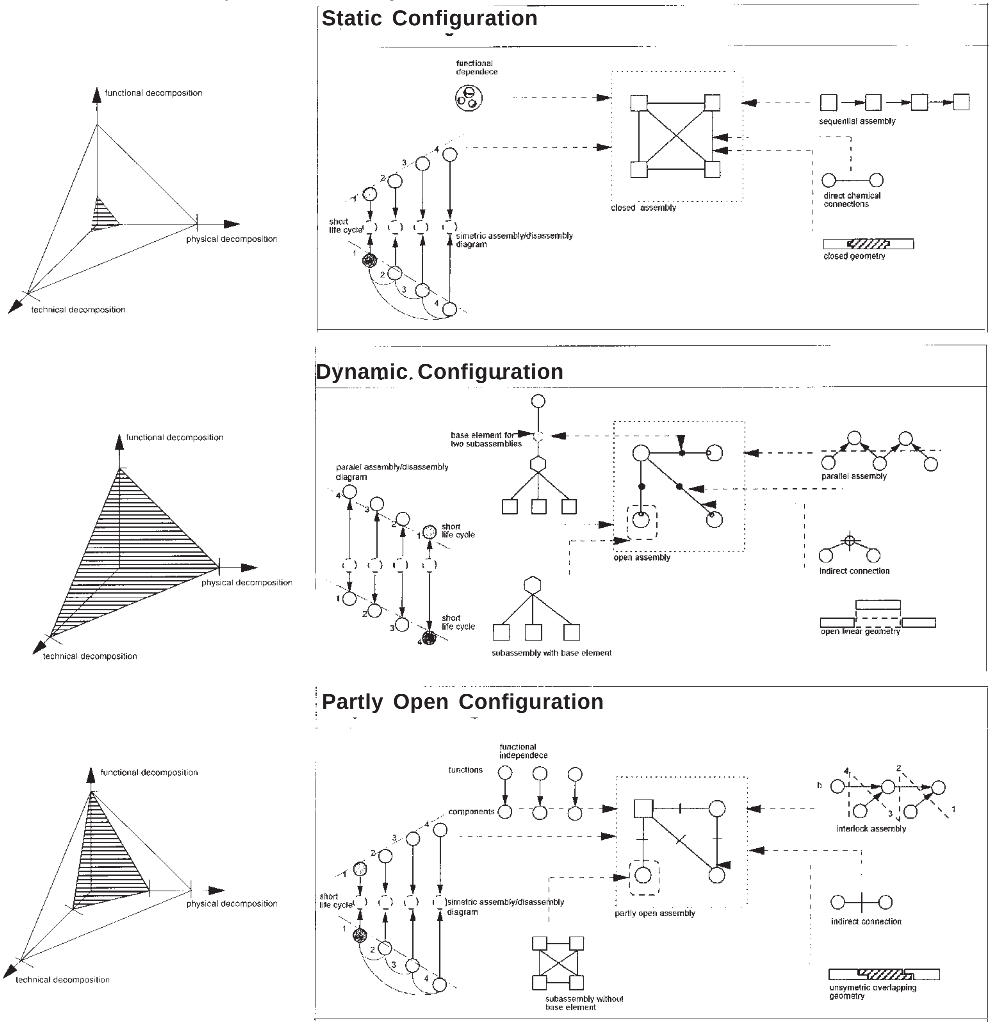
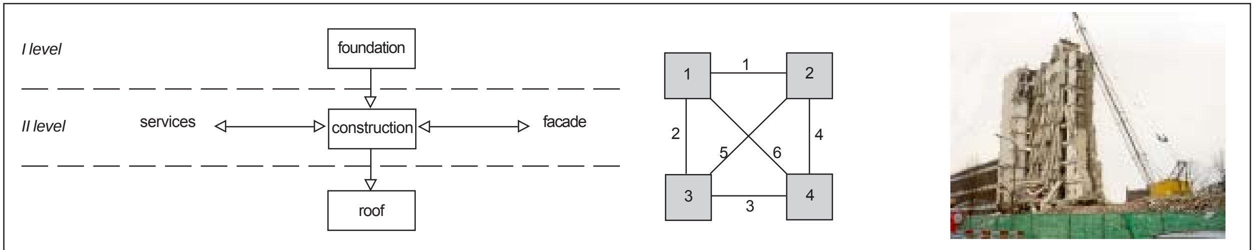


Figure 5.26: Three types of configurations with respect to disassembly potential, represented by major design aspects that influence elements of configuration design and consequently the type of configuration.Elements of configuration design graded from 0 (low disassembly potential) to 1 (high disassembly potential).

Static configurations are characterised by maximal integration and dependency between building components, and is caused by:
(i) Material levels that do not correspond to independent building functions,
(ii) hierarchy of assembly not related to component service life and expected time to obsolescence,
(iii) complex relational patterns presenting high levels of dependency between elements
(iii) application of sequential assembly sequences,
(iv) design of integral joint types (components are shaped in such a way that bringing them together forms a joint), and
(v) use of chemical connections.

Such structures do not have the potential for functional, technical, and physical decomposition, which define the potential for a structure to be transformed. They define a category of non-transformable structures (Figure 5.27). Traditionally, building elements are closely related to one another, with no respect to the different functions and life cycles they may have. This creates maximum integration at joints. Such traditional buildings often have a great dependency between the load bearing structure, façade, partitioning walls, and installations, due to their closed hierarchical assembly. Such buildings usually end up being demolished.



Partly decomposable structures are dependent on a design strategy in which the hierarchy of fixed and flexible elements is adjusted accordingly. Fixed elements are elements with high levels of flexibility that allow spatial and functional changes, and high durability.Flexible elements are elements frequently exposed to change.Flexibility of such structures is restricted to the designed capacity of fixed elements and the type of flexibility strategically chosen. Such structures are partially decomposable because fixed parts of the structure are not designed for functional, technical, and physical decomposition. Figure 5.28

Figure 5.27:Functional and relational dependency of static configuration.

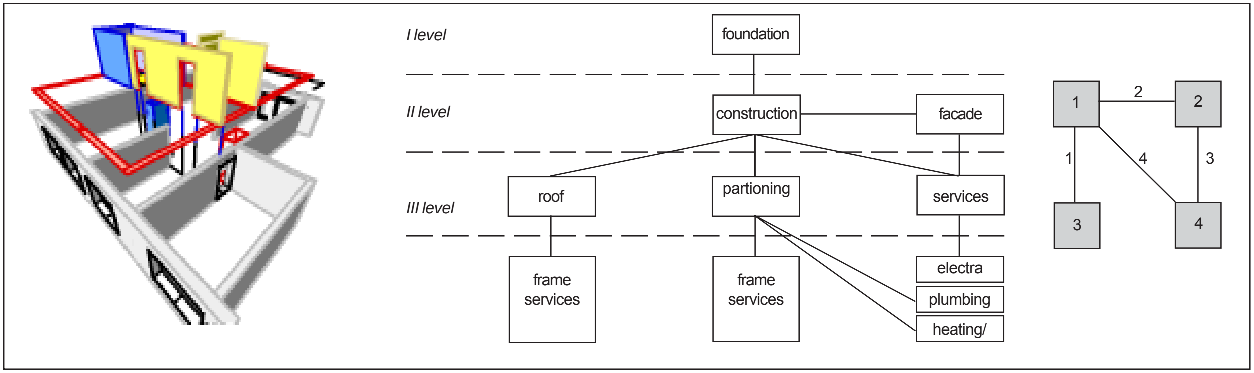


Figure 5.28:Functional and relational dependency of partly open configuration.

Dynamic structures

Dynamic configurations, as opposed to static configurations, have open assemblies with independent sub-assemblies that represent independent functions.

Main characteristics of *dynamic configurations* are (i) Separation of material levels, which correspond to independent building functions, (ii) creation of open hierarchy of distinct sub assemblies, (iii) use of accessory joint types that require additional parts to form the joint between components, (iv) application of parallel instead of sequential assembly/disassembly processes, and (v) use of mechanical connections in place of chemical connections. Such building configurations provide the precondition for independence and exchangeability of building components, and accordingly, their reuse, reconfiguration, or recycling through functional, technical, and physical decomposition (Figure 5.29).

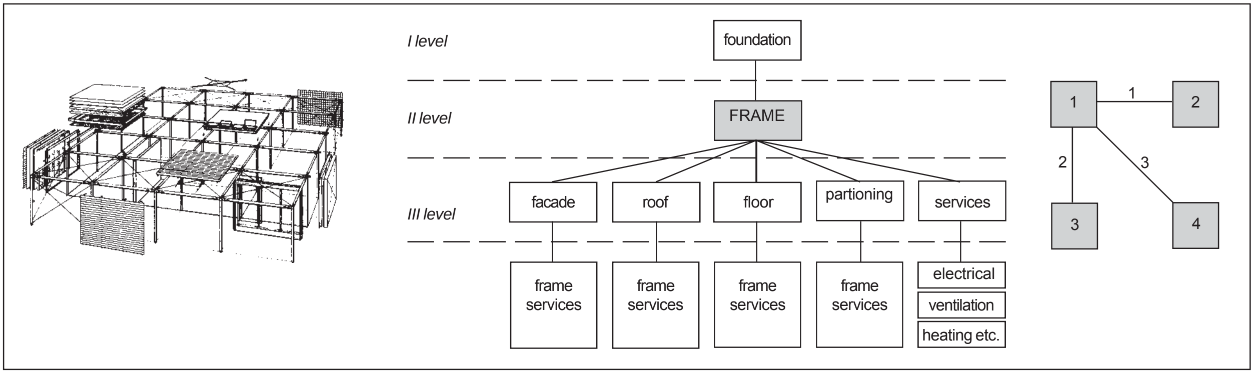


Figure 5.29:Functional and relational dependency of dynamic configuration.

5.6 CASE STUDY THE BUILDING XX

Project XX is an experimental office building designed from the outset for sustainability.

Conventional approaches to sustainable building are usually related to longlasting buildings whose economical life cycle should be 50-60 years. Unlike the conventional approach to durable building which is focused on long duration of buildings and their materials, Project XX focuses on short life cycle of building (20 years). That means that either all building parts will last 20 years or they will easily be disassembled back into components and recycled or reused in new combination after 20 years. One could ask oneself weather such approach would deliver lower quality buildings made of lower quality materials. The answer to such question could be found in the statement by architect Jouke Post who described the strategy of making of Project XX through categorisation of all materials into three groups: (Post 2001)

- The first priority were elements that could last 19,5 years and remain in perfect condition,
- the second priority were elements, that could be easily reused, and
- the third priority were materials that could be taken back and recycled.

Figure 5.31: post and beam structure of the XX building

Foundations

According to the first proposal the building was supposed to lay on steel pillars which could be easily taken out from the ground, but later for economic reasons the final choice was made for a concrete foundation (in which the concrete is made of 20% recycled aggregate).

Structural Frame

One of the main characteristics of this building is its structural frame that is made from wood and steel. Decisions to use a wood as structural material was made after analysis of other structural materials such as: steel, aluminium, concrete, stone, synthetic materials and cardboard. The materials were analysed in relation with their durability, strength, costs, recyclability, and general experience in working with them. After the competitive analysis done by ABT, wood proved to have the best characteristics.

The structural frame of the building is made of laminated “Swedlam LVL” timber

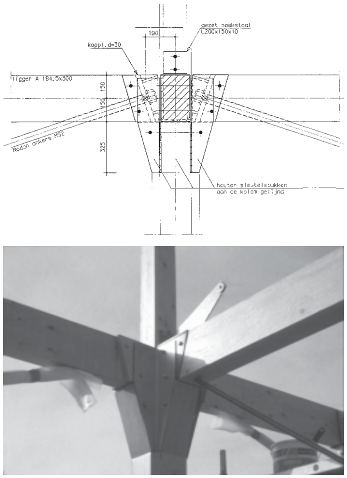
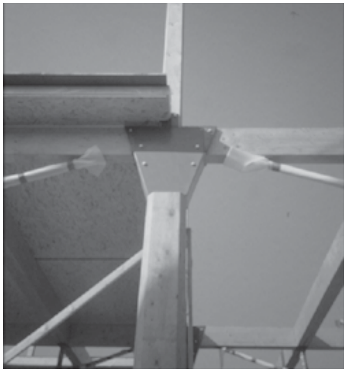
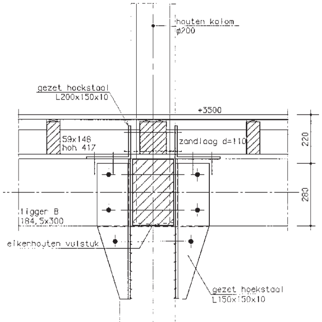


Figure 5.32: column – beam connection





source J.Post-XX Architecten

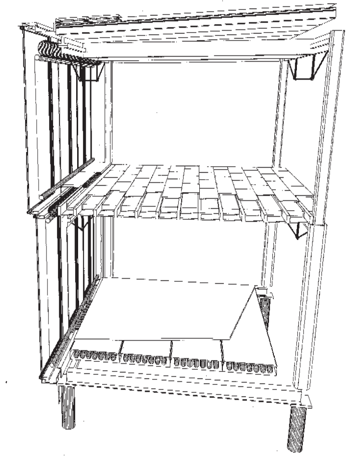
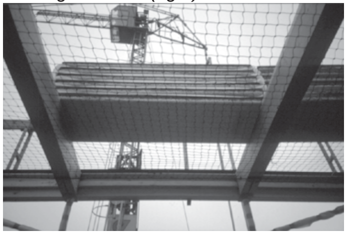


Figure 5.33: Left, prefabricated-removable floor elements placed on the first floor and 3D representation of theXX building structure (right)



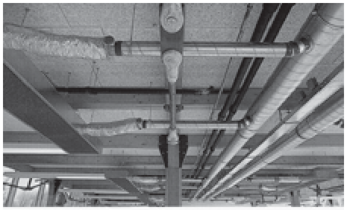


Figure 5.34: figure shows assembly of removable roof elements, assembled façade and installation components

with its columns / 30x30x350 cm on the ground floor and 20x20x350 cm on the first floor / and beams reinforced with standoff steel bar lower chords. The frame is stiffened by wind bracing on the ground floor, first floor, and on the roof. The use of vacuum pressed wood has saved 25% of the raw materials (Figure 5.31).
The elements used to connect columns and beams are: steel plates, steel pins and bolts (Figure 5.32).

Floor construction on the first level consists of wooden sandwich panels (600x500 cm) filled with sand (Figure 5.33).
Acoustical problems are solved by the introduction of thick layer of sand and 1cm of felt, which is put on contacts between the secondary beams and the top floor layer.
The floor on the ground is made of concrete with 20% of recycled aggregate. It is separated from thermal isulation with thin foil so that it could be easily replaced and recycled in the future.

Roof construction is made of fibrous concrete and recyclable roof covering. A bitumen layer, which is only partially fixed to the thermal isulation and makes it also recyclable (Figure 5.34 above).

Facade
The buildings envelope is made of glass façade. Triple pre-assembled glass

segments (2x3,5m) from “Saint Roch” were chosen for this façade. The glass segments are placed in the wooden frame. All connections are kit-lose. The glass panes are fixed with screws to the façade frame. The wooden facade frames have been placed on the steel consoles which are attached to the main structure. This makes the facade independent of the main frame. At the same time the upper side of the same frame is screwed to the floor panels on the first floor. That means that changes to the floor can affect the façade.
The glass façade, carton ventilation pipes and sunscreens which are placed inside some 44cm away from the wooden façade frame are integrated into a climate façade. The climate façade developed by Leijendeckers provides energy saving (Figure 5.34 middle).

Installations
All horizontal ducts for air condition_are made of cardboard and attached to the T-profiles that are connected to the floor panels (Figure 5.34 bellow). The channel for the electrical installations and the holes for the water pipes are pre-made in the floor panels.
(SEV 2001)

5.7 CONFIGURATION OF THE BUILDING XX

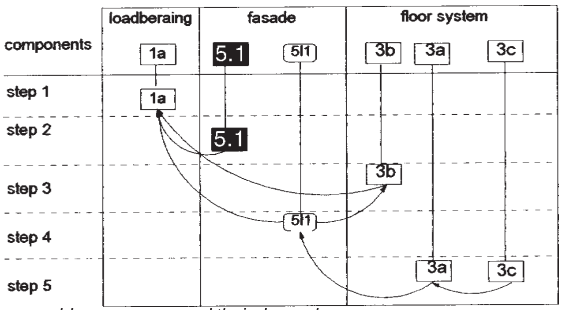
Office building XX is designed to stand for 20 years with the goal that its components and materials are then reused or recycled. Its main building functions are defined as separate systems and produced by separate producers so that the contractor had only a managing role. Besides the floor and wall finishes all materials were pre-made and dry assembled, which makes disassembly possible.Tthe whole building is designed so that it can be disassembled at the end of its designed life cycle.
Reassembly is the ultimate form of reusing and recycling. However, if the configuration of the building is analysed from the transformational point of view then besides the disassembly aspects the replaceability of changeable parts and their reassembly alsol determines the transformation capacity of the building.
If modification should take place before the end of the design life of the XX building then the configuration should be dynamic.

codes	systems specification
1	floor system ground floor - kanaal plat
1a.	floor system ground floor - console
1b.	floor system ground floor Š isolation of the console
1c.	floor system ground floor - isolation of the kannal plat
1d.	floor system ground floor Š enclosing of the console
1e.	floor system ground floor Š inside finishing of the console
2	load bearing frame - post and beam structure
2a.	load bearing frame - console 1st floor
2b.	load bearing frame Š roof console
3	floor system second floor Š wooden sandwich panels
3a	floor system second floor Š send as isolating material
3b	floor system second floor Š wood finishing
3c	floor system second floor Š acoustic platoon
4	roof system - fibrous concrete
4a	roof system Š bitumen
4b	roof system Š roof cover
4c	roof system Š acoustic platoon
5 I1	fa¨ade system first floor Š Intermediary
5.1	fa¨ade system first floor Š wooden frame
5a1	fa¨ade system Š triple glass panels
5b1	fa¨ade system Š aluminium fixings
5 I2	fa¨ade system first floor Š Intermediary
5.2	fa¨ade system first floor Š wooden frame
5a2	fa¨ade system Š triple glass panels
5b2	fa¨ade system Š aluminium fixings
6	partitioning wall system Š metal studs
6a	partitioning wall system Š isolation
6b	partitioning wall system Š gypsum panels
6c	partitioning wall system Š finishing
7	electrical installations Š base duct
7a	electrical installations Š distribution net
7b	electrical installations Š outlets
8ŹŹŹŹŹ	water installations Š distribution net
8a	water installations Š outlets
9	ventilation distribution net
9a	ventilation outlets

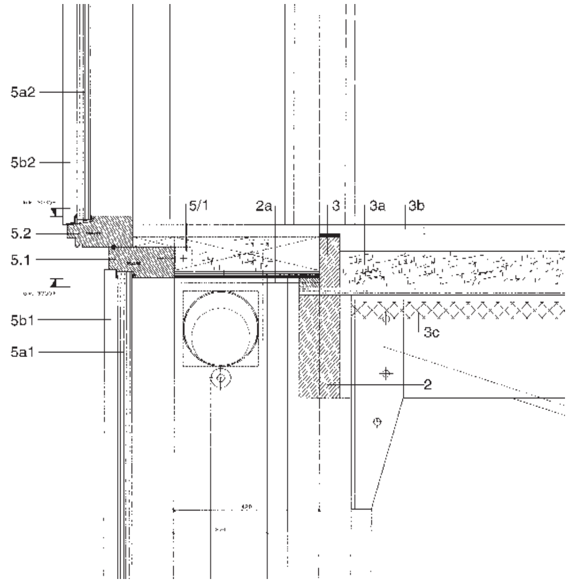
Figure 5.35: detail - integration of main assemblies within xx configuration (source J.Post-XX Architecten)

Relational diagram right shows position of relations between different functional groups

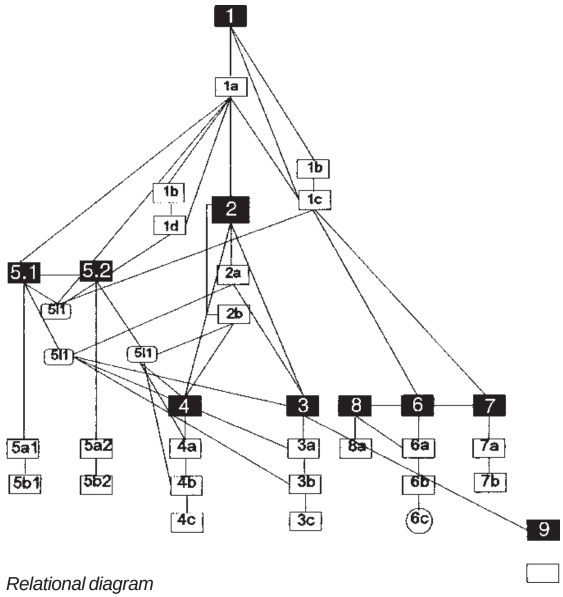
diagram below left shows dependecy of building components during assembly operation



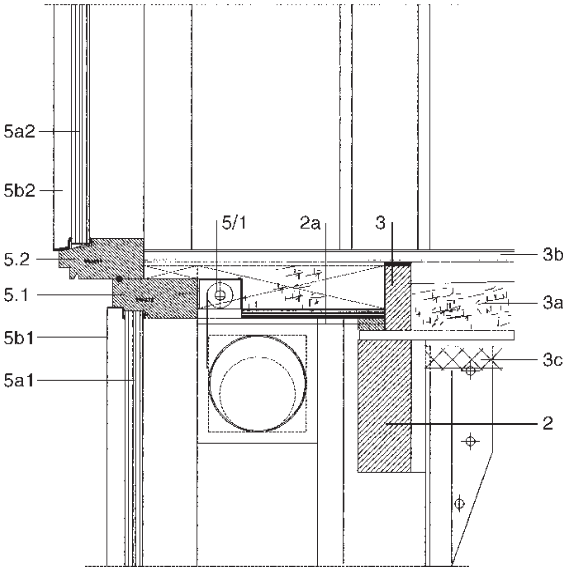
assembly sequences and their dependence



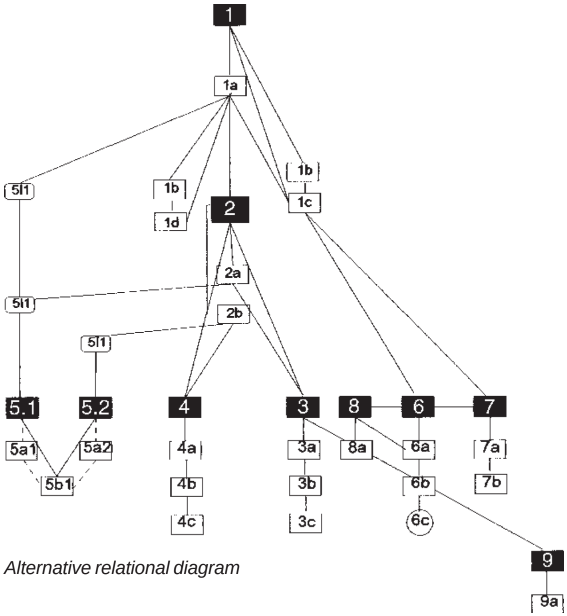
detail - integration of main building assemblies



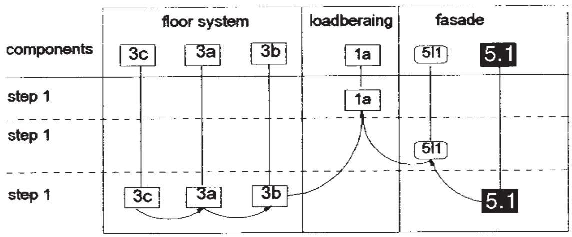
Relational diagram



Alternative detail - integration of main building assemblies



Alternative relational diagram



Alternative assembly sequences and their dependence

Figure 5.36:
Alternative configuration of the XX building represented through a detail - integration of main assemblies within xx configuration, relational diagram and an assembly sequences diagram.

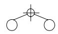
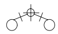
5.7.1 Configuration on the building level

The relational diagram in figure 5.35 represents the partially open hierarchical relations between the building systems. The diagram shows that the façade has a greater dependency that most of the other systems, primarily because of the additional relation with the roof element (elements marked as 4, 4a and 4b in diagram).

When analysing the structure of independent sub-assemblies and their relations, one can recognise certain patterns of dependency which are created not only between the façade and the roof, but also between the façade and floors (elements marked as 3, 3a and 3b in diagram).

The figure 5.35 indicates the problem within the XX configuration on the building level when the existing façade system must be replaced with a different system. In other words, in order to replace an existing façade system, seven relations must be cut meaning that parts of the roof and the floor should be removed.

This is caused primarily because the intermediary between the façade and the main frame is placed in the sub-assembly of the floor and the roof. Lack of accessibility to this intermediary results in the partial removal of the floor finishing

no.	relations	connection	disassembly	demolition	reuse	recycle	waste in constr.	waste in disassembly
1	construction-façade		x		x	x	~0% ~0%	~0% ~10%
2	conctruction install..		x		x	x	~0% ~0%	~0% ~0%
3	construction - finishing			x			~0%	~0%
4	construction part.walls		x		x	x	~0%	~0%
5	construction-roof		x			x		
6	roof-roof finnishing		x			x		
7	partt.wals - install		x		x	xx		
8	floor-install			x				~100%

and the isulation, as well as roof and roof finishing, in order to remove the façade system. An ideal case would be to provide accessibility to the fixings of the façade so that the other parts of the building can stay intact during replacements of the façade. Providing accessibility to the intermediary can create an open hierarchical relational diagram. One possible way of achieving this is shown in the Figure 5.36

5.7.2 Configuration on the system level

Beyond the building level one can look into the next level of configuration: namely, the system level. On this level, replaceability of the component and elements within the system are analysed (Figure 5.37). If we go back to the façade system of the XX building we can recognise that independent sub-assemblies composed of wooden frames (base elements), glass panels and aluminium fixings are put together that form system components. The relational diagram in figure 5.38 indicates that the base elements of systems component (elements marked as 5.1 and 5.2 in the diagram)have a great level of dependency since all are related to each other. For this reason replaceability of one sub-assembly is impossible without demolition of surrounding sub-assemblies.

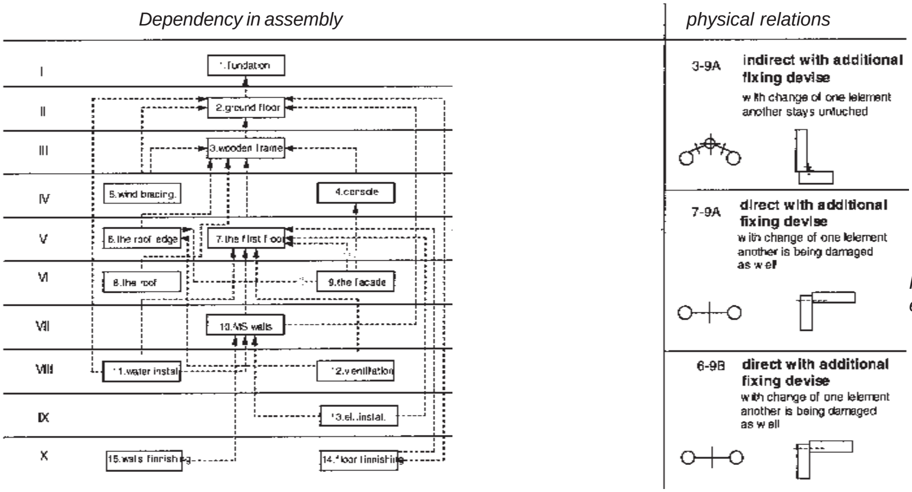
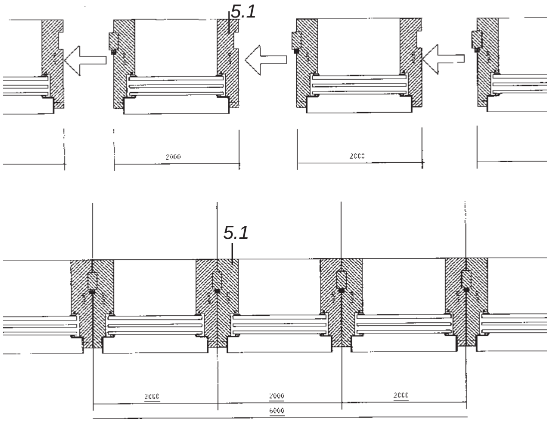
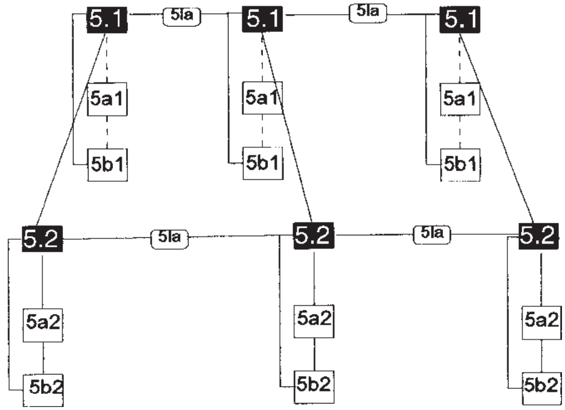


Figure 5.37: Dependency of the façade element 9.

The figure 5.38 present the assembly of the façade components into a façade subsystem. The connection between two components is provided via a third element, which is placed in-between two window frames. Therefore the assembly sequence of such connections becomes linear and creates a linked dependency of each newly assembled element with the previous one.

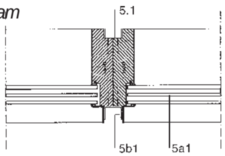
figure 5.38: Configuration of the façade system of XX building represented by the assembly sequences of systems components and the relational diagram. Left assembly direction, right relational diagram

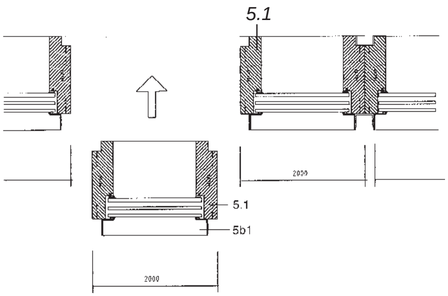


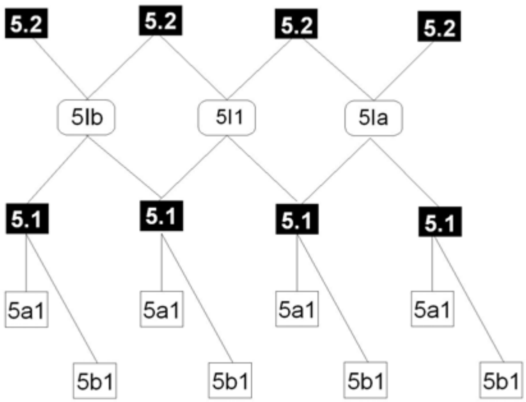


Relational diagram

figure 5.39: Alternative configuration of the façade system of the XX building that has a higher disassembly potential of system components.
Left assembly direction, right relational diagram







Alternative relational diagram

Due to such a connection, which is followed in a sequential assembly, one element of the façade can not be independently taken out of the façade sub-system. Just like on the building level, the inability to access the fixing element results in a lack of disassembly potential for the base elements. This can be seen in relational diagram in the figure 5.38. Such static configuration can be transformed into open, if accessible intermediary is provided, as shown in the Figure 539 .

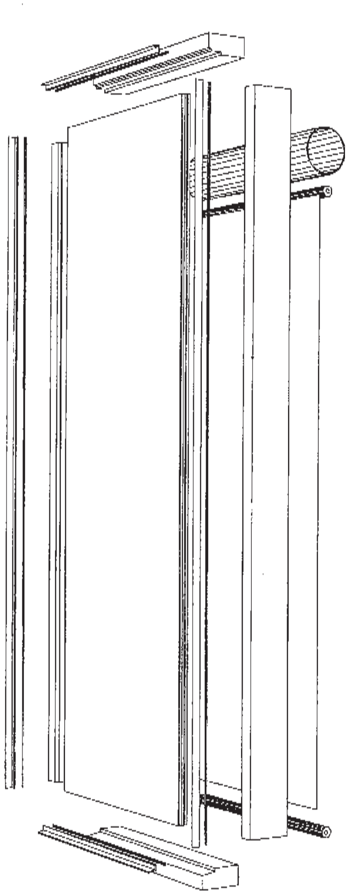
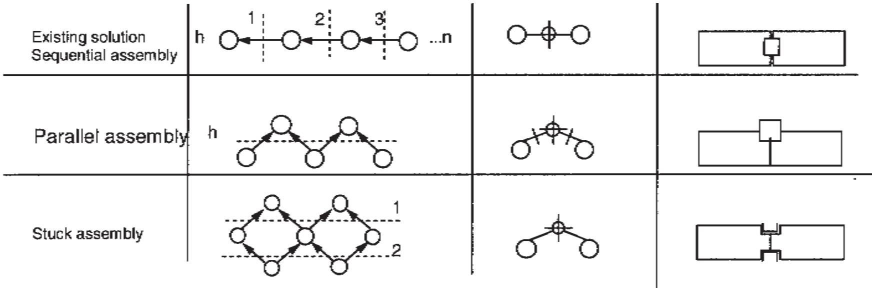
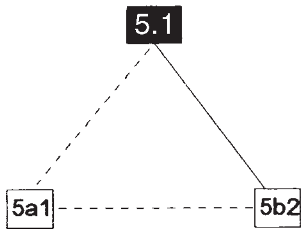


Figure 5.40: XX Fasade component

Thus, the more suitable solutions for the easy disassembly of one façade sub-component should be looked for in parallel assembly in combination with an independent intermediary. Two alternative principal solutions are shown in the following table.





5.7.3 Configuration on the component level

The next level of systems configuration is the component level. The façade components of XX building are made of three elements. The base element, which is a wooden frame, filling, which is the glass panel, and aluminium strips that fix the glass panel. (Figure 5.40)

A totally dry assembly is used and the aluminium strips are fixed with screws to the base frame. Components within one assembly can be disassembled independently of the component in other assemblies. Taking into account that wood, glass, and aluminium have different functions and different life cycles their independence and exchangeability created within this configuration makes it the most representative example of design for disassembly in the design of XX building.

The way that these three domains are defined determin the disassembly characteristics of the building configuration.

Based on this analysis the graphical representation of transformation potential of the façade system is shown in figure 5.41 with respect to:

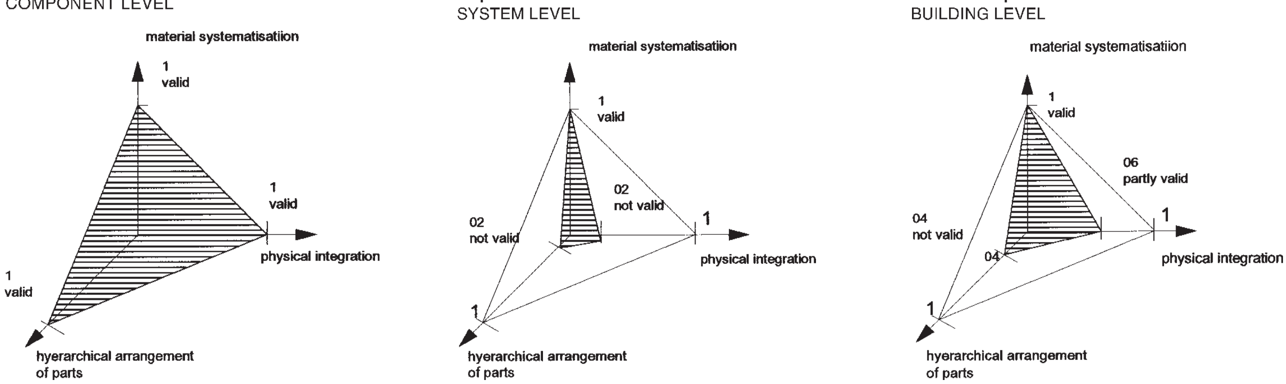
1. integration of the façade on the building level,
2. reconfiguration and reuse on the system level
3. reconfiguration, reuse, and recycling on the component level

Three design domains that determine type of configuration is graded (with respect to disassembly potential) from 0 (low disassembly potential) to 1 (high disassembly potential). (Figure 5.41)

1. Transformation capacity on the building level is marked as partially transformable since the façade system cannot be removed without removing the other components which are part of the roof and the floor system.
2. Transformation capacity on the system level is marked as non- transformable since one component cannot be replaced without demolishing and removing other components within the system. Although the transformation capacity in relation to the systematisation of material levels is defined as very suitable the total transformation is defined as not valid TC=0.4 In order to improve the configuration, the arrangement between the components and connections should be redesigned.
3. Transformation capacity on component level is market as transformable since all elements within the component can be removed and reused or recycled.

The computational evaluation model is discussed in Chapter 6.

Figure 5.41: Disassembly characteristics of three design elements of configuration



Chapter 6

Assessment of Transformation Capacity by means of a Knowledge Model

Disassembly Potential of the building structure is an indicator of buildings Transformation Capacity

INTRODUCTION

This chapter discusses a knowledge model developed to assess the Transformation Capacity (TC) of building structures based on their disassembly potential.
Eight aspects of deconstruction and their sub-aspects have been used as the basis for the model.
The influence that each aspect has on TC has been built into the model by defining weighting factors for each relation between the model variables.

The model is based on fuzzy input data that represent linguistic variables. Traditional linear models, which are based on correlation co-efficiency, have a high level of imprecision when dealing with such data. For this reason the model has been developed using fuzzy logic, which is more accurate when dealing with such data.
The advantages of fuzzy models over traditional models is briefly discussed in this chapter.
Two test case studies and interpretation of their results are discussed.
These results have been compared with results of their Life Cycle Assessments (LCA). This comparison shows that results gained by assessment of TC are also indicators of the environmental efficiency of structures. A higher TC means lower environmental impact from a building configuration.

6.1 CONCEPTUAL FRAMEWORK OF THE KNOWLEDGE MODEL

There were few attempts in a past to assess flexibility of buildings or their parts; for example, the Capacity to Change (CTC) index by the OBOM research group presented in a report of OBOM research group in 1992 (Brouwer at all 1992). The report suggested that the Dutch Real Estate norm, which evaluates the quality of real-estate properties should include flexibility aspects as well. It was proposed that the following three aspects should be considered: separations of levels of decision making being site, support and infill, evaluation of load bearing structure in relation to building services, and dependences between building elements. Although the CTC index was not developed further than that report, the idea has been found challenging for many real estate companies in the Netherlands such as ING bank, Rabo Bank etc. A Model developed to measure the flexibility of installation services is the Flexis modal by Rob Gerards. This model addressed aspects of spatial and technical flexibility that installation systems deal with such as position, accessibility to services, and over capacity of systems. This was to allow for different spatial typologies. (Geraedts 1995) Another model by Elma and Sanja Durmisevic was developed to assess spatial transformation in relation to technical aspects, such as the span of load-bearing construction, position of main installation net, position and replaceability of distribution installation net, and replaceability of partitioning walls. (Zoet 2000)
However, taking into account the growing concerns about the efficiency of use of building materials coupled with growing demand for development of building systems that are adaptable to changing user needs, it becomes necessary to assess the transformation capacity of buildings, which is an indicator of their disassembly potential. By doing this one can better judge the sustainability of design solutions, since disassembly is related to reconfiguration, reuse, and up cycling of building parts.
The assumption is made that one can profit from high disassembly potential by saving materials, embodied energy, landfill costs, costs of purchasing new materials and greater spatial adaptability of buildings.

This knowledge model was developed using information acquired from buildings, and deals with the performance indicators of transformable structures. These are defined by the design criteria of: independence and exchangeability of building elements. A building or system can be transformed if its parts can be defined as independent parts of a building structure, and if the interfaces between parts are demountable. Independence of building products is determined by decomposition of material levels and technical decomposition; while exchangeability is determined by physical decomposition. Accordingly, indicators of independence are: functional decomposition, systematisation, hierarchy, base element specification, and life cycle coordination. Indicators of exchangeability are: type of connections, assembly sequences, and geometry of product edge.

The framework of the knowledge model is shown in the figure below.

The framework can be used as decision support model for the design of transformable buildings, as well as an evaluation model for a building's TC.

The knowledge model distinguishes between three design domains of configuration (material, technical, and physical decomposition), which treat the various aspects described above. Although these three decision groups can be distinguished, they cannot be separated. The decision dependency between these groups is shown in the figure 6.01.

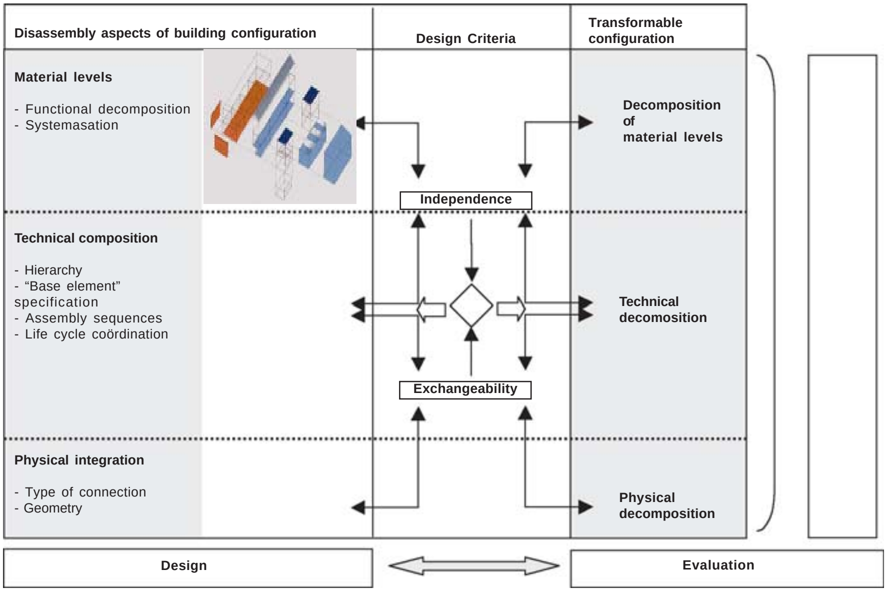


Figure 6.01:A conceptual framework of the decision support / evaluation model

A material is proposed only if a feasible technical decomposition can be defined. A proposed technical decomposition is valid only if a feasible interface can be defined.

The input data for the model are collected based on expert assessment of the different criteria, which have an impact on the disassembly potential of structures. The inputs are not fixed measures - they differ from project to project. For that reason inputs are defined as independent variables. The model deals with 17 independent variables and 14 dependent variables (Figure 6.02b). Dependent variables represent collected knowledge, which represent functional, technical, and physical composition/decomposition of one structure.

The knowledge model with its independent and dependent variables and relations has a hierarchical structure, and can be described through four levels of dependencies (Figure 6.02a).

- *First level:*
  The input level, that consists of sub-aspects (sub-components) and a specification of their impact on the main aspects.
- *Second level:*
  Represents a specification of the impact that main aspects have on three components of the building configuration: material levels, hierarchy, and interface]. The weights define the hierarchy of importance of each aspect.
- *Third level:*
  A specification of the impact that components of the building configuration have on the indicators of transformation: independence and exchangeability.
- *Forth level:*
  A specification of the impact that indicators of transformation have on the disassembly potential, which represents the TC of a structure.

Tables 6.1,6.2, and 6.3 show the principles for the collection of the data on the input level of the model. It represents consideration of all sub-aspects of DfD that were discussed in Chapter 5. Assessed sub-aspects (level 0) are integrated into the knowledge model by adding the weighting factor that presents the impact of each sub-aspect on the main aspect of DfD. Further composition of the model from level 0 (input level) to level 4 (assessment of TC) will be discussed in the following sections.

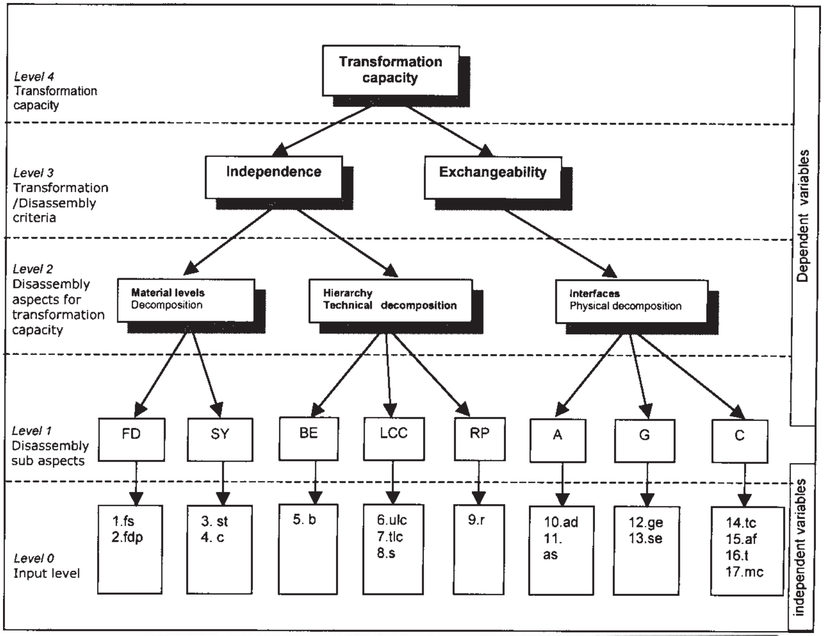


Figure 6.02a: hierarchical structures of the Knowledge Model

nr.	Design for Disasembly Aspects	nr.		Determining Factors
1	FD (Functional decomposition)			
		1.1.	fs	(functional separation)
		1.2.	fdp	(functional dependence)
2	SY (Systematisation)			
		2.1	st	(structure of material levels)
		2.2	c	(type of clustering)
3	BE (Base elements)			
		3.1	b	(type of base element)
4	LCC (Life cycle coordination)			
		4.1	ucl	(use life cycle coordination)
			tcl	(technical life cycle coordination)
			s	(coordination of life cycle and size)
5	RP (Relational pattern)			
		5.1	r	(type of 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	(morphology of joints)

Figure 6.02b: list of design for disassembly aspects and corresponding sub-aspects

				grading
FD FUNCTIONAL DECOMPOSITION	functional separation	fs 01	separation of functions	1
		fs 02	integration of functions with same lc* into one element	0,6
		fs 03	integration of functions with different lc* into one element	0,1
			fs = [fs1+ fs2 + ….fs(n)] / n	
	functional dependence	fdp 01	modular zoning	1
		fdp 02	Planed interpenetrating for different solutions (overcapacity)	0,8
		fdp 03	Planed interpenetrating for one solution	0,4
		fdp 04	Unplanned interpenetrating	0,2
		fdp 05	total dependence	0,1
			fdp = [fdp1+ fdp2 + ….fdp(n)] / n	
			FD = fuzzy calculation based on "fs" and "fdp" and their weighting factors	
SY SYSTEMATISATION	structure and material levels	st 01	components	1
		st 02	elements / components	0,8
		st 03	elements	0,6
		st 04	material / element / component	0,4
		st 05	material / element	0,2
		st 06	material	0,1
			st = [st1+ st2 + ….st(n)] / n	
	clustering	c 01	clustering according to the functionality	1
		c 02	clustering according to the material life cycle	0,6
		c 03	clustering for fast assembly	0,3
		c 04	no clustering	0,1
			c = [st1+ st2 + ….st(n)] / n	
			SY: = fuzzy calculation based on "st" and "c" and their weighting factors	
BE BASE ELEMENT	base element specification	b 01	base element- intermediary between systems /components	1
		b 02	base element- on two levels	0,6
		b 03	element with two functions (be. and one building function)	0,4
		b 04	no base element	0,1
			b = [b1+ b2 + ….b(n)] / n	
			BE = fuzzy calculation based on "b" and its weighting factor	
LCC LIFE CYCLE CO-ORDINATION	use life cycle/ coordination (1)- assembled first (2)- second	ulc 01	long LC (1) / long LC (2) or short LC(1) / short LC(2)	1
		ulc 02	long LC(1) / short LC(2)	0,8
		ulc 03	medium LC (1) / long LC (2)	0,6
		ulc 04	short LC (1) / medium (2)	0,3
		ulc 05	short (1) / long LC (2)	0,1
			ulc = [ulc1+ulc2 + ….ulc(n)] / n	
	technical life cycle/ coordination	tlc 01	long LC (1) / long LC (2) or short (1) / short (2) or long (1) short (2)	1
		tlc 02	medium LC (1) / long LC (2)	0,5
		tlc 03	short LC (1) / medium LC (2)	0,3
		tlc 04	short LC (1) / long LC (2)	0,1
			tlc = [tlc1+ tlc2 + ….tlc(n)] / n	

Table 6.1: evaluation of functional decomposition, systematisation, base element specification and life cycle coordination of buildings assemblies with respect to independency and exchangeability of components.

				grading
LCC LIFECYCLE CO-ORDINATION	**lifecycle of components and alelents in relation to the size** (1)- assembled first	s 01	small element (1) / short LC or medium component (1) / short LC	**1**
		s 02	big component (1) / long L.C.	**1**
		s 03	big (small) element (1) / long LC	**0,8**
		s 04	big component (1) / short LC	**0,4**
		s 05	material (1) / short L.C.	**0,2**
		s 06	big element / short L.C. or material / short life cycle	**0,1**
			s = [s1+ s2 + ….s(n)] / n	
			LCC = fuzzy calculation based on "ulc","tlc" and "s" and their weighting factors	
RP RELATIONAL PATTERN	**position of relations in relational diagram**	r 01	vertical	**1**
		r 02	horizontal in lower zone of the diagram	**0,6**
		r 03	horizontal between upper and lower zone of the diagram	**0,4**
		r 04	horizontal in upper zone	**0,1**
			r = [r1+ r2 + ….r(n)] / n	
			RP = fuzzy calculation based on "r" and its weighting factor	
A ASSEMBLY	**assembly direction based on assembly type**	ad 01	parallel - open assembly	**1**
		ad 02	stuck assembly	**0,6**
		ad 03	base el.in stuck assembly	**0,4**
		ad 04	sequential seq.base el	**0,1**
			ad= [ad1+ ad2 + ….ad(n)] / n	
	assembly sequences regarding material levels (1)- assembled first (2)- second	as 01	component (1) / component (2)	**1**
		as 02	component (1) / element (2)	**0,8**
		as 03	element (1) / component (2)	**0,6**
		as 04	element (1) / element (2)	**0,5**
		as 05	material (1) / component (2)	**0,3**
		as 06	component (1)/material (2)	**0,2**
		as 07	material (1) / material (2)	**0,1**
			as= [as1+ as2 + ….as(n)] / n	
			A = fuzzy calculation based on "ad" and "as" and their weighting factors	
G GEOMETRY	**geometry of product edge**	gp 01	open linear	**1**
		gp 02	symmetrical overlapping	**0,8**
		gp 03	overlapping on one side	**0,7**
		gp 04	unsymmetrical overlapping	**0,4**
		gp 05	insert on one sides	**0,2**
		gp 06	insert on two sides	**0,1**
			gp= [gp1+ gp2 + ….gp(n)] / n	
	standardisation of product edge	spe 01	pre-made geometry	**1**
		spe 02	half standardised geometry	**0,5**
		spe 03	geometry made on the construction site	**0,1**
			spe= [spe1+ spe2 + ….spe(n)] / n	
			G = fuzzy calculation based on "gp" and "spe" and their weighting factors	

Table 6.2: evaluation of relational pattern, assembly procedures, and geometry of buildings assemblies with respect to independency and exchangeability of components.

				grading
C	type of connection	tc 01	accessory external connection or connection system	1
		tc 02	direct connection with additional fixing devices	0,8
		tc 03	direct integral connection with inserts (pin)	0,6
		tc 04	direct integral connection	0,5
		tc 05	accessory internal connection	0,4
		tc 06	filled soft chemical connection	0,2
		tc 07	filled hard chemical connection	0,1
		tc 08	direct chemical connection	0,1
			tc= [tc1+ tc2 + ….tc(n)] / n	
CONNECTIONS	accessibility to fixings and intermediary	af 01	accessible	1
		af 02	accessible with additional operation which causes no damage	0,8
		af 03	accessible with additional operation / causes reparable damage	0,6
		af 04	accessible with additional operation/causes partly reparable damage	0,4
		af 05	not accessible - total damage of bought elements	0,1
			af= [af1+ af2 + ….af(n)] / n	
	tolerance	t 01	high tolerance	1
		t 02	minimum tolerance	0,5
		t 03	no tolerance	0,1
			t= [t1+ t2 + ….t(n)] / n	
	morphology of joint	mc 01	knot (3D connections)	1
		mc 02	point	0,8
		mc 03	linear (1D connections)	0,6
		mc 04	service (2D connection)	0,1

mc= [mc1+ mc2 + ….mc(n)] / n

C = fuzzy calculation based on "tc","af","t" and "mc" and their weighting factors

Table 6.3: evaluation of connections of buildings assemblies with respect to independency and exchangeability of components.

6.1.1 INTERPRETATION OF THE RESULTS

The hypotheses of this research is that greater TC results in lower environmental impact, since high transformation ability means that buildings can be adopted to the new requirements, and that their components and materials can be replaced, reused, reconfigured, and recycled.

The discussion in this chapter is based on the assumption that greater disassembly potential means greater flexibility and environmental efficiency. This leads to greater sustainability.

The aspects are aranged in such way that each aspect that result in demolition of components has values between 0.1 and 0.3.

Aspects that indicate partial demolition and reconfiguration have been graded between 0.3 and 0.6. Finally, aspects that indicate disassembly with possible reuse, reconfiguration, and recycling have values between 0.6 and 0.9.

Such specifications give a framework of relations between the TC and the environmental efficiency of configurations. According to the defined framework, all building structures can be grouped into three categories:

Category 1: The first category of transformation has high disassembly potential where both indicators of transformation (independence and exchangeability) have more than 70% of the highest possible value. These result in a TC > 0.67. Accordingly, less than 25% of construction waste is produced during deconstruction.

Category 2: The second category has medium disassembly potential were both indicators have between 33 and 70 % of their highest possible value. This results in 0.33 <TC < 0.67. Accordingly, between 20-80% of construction waste is produced during deconstruction

Category 3: The third category has a low disassembly potential where both indicators have less than 33% of their highest possible values. This can be recognised as a standard waste-stream in construction. Consequently TC < 0.33. Accordingly, more than 80% of construction waste is produced during deconstruction.

The assessment of each disassembly factor discussed in Chapter 5, can be represented in a radial diagram. (See figures 6.03). If all scores are connected, a closed figure is created. The most favourable value for each disassembly aspect is set as value " 1 ". The diagram represent a radial diagram that, indicates a transformable structure. This is close to the outer line of the graphic. A figure that is close to the middle of the circle indicates that these design aspects score poorly when it comes to disassembly and transformation.

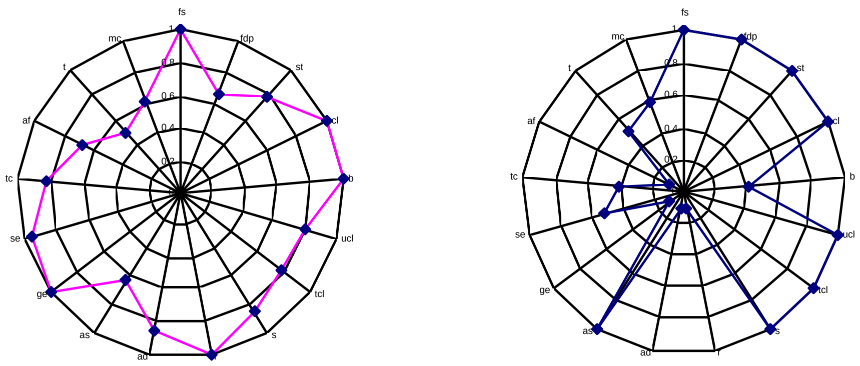


Figure 6.03: value of disassembly factors in XX building judged upon total disassembly, right value of disassembly factors of XX facade system judged upon replaceability

Such assessment is appropriate for different building or system structures regarding their disassembly potential and TC.

The graphic shows which of the solutions are most favourable for transformation, but it does not reduce a designer's assessment conflict, since each design aspect has a different level of influence on the final measure of transformation. Introducing individual weighting of relations between aspects and result can solve this. This is the case with the knowledge model presented in this chapter. Thus, the models deal not only with 17 independent and 14 dependent variables, but also with 40 relations between the variables.(See Diagram 6.1) These relations were given weights, which take care of the hierarchy of influence that different variables have on the final result.

For example, material decomposition, which is on the second level of the model hierarchy, is defined as the function of functional decomposition (FD), life cycle coordination between the components (LCC), relational pattern (RP), level of systematisation of elements into independent clusters (SY), and connections between the elements. However, the highest influence on the material decomposition, which is the key to the independence of the components,

SPECIFICATION OF WEIGHTING FACTORS

level 4	weights	level 3	weights	level 2	weights	level 1	weights
DP = TC =	I : 0.9	**I =**	SP : 1	**ML =**	FD : 1	**FD =**	fs : 0.9
	E : 0.9		HR : 1		LCC: 0.6		fdp : 0.7
					RP : 0.5		
		E =	INT : 1		SYS :0.5		
					C : 0.3	**SYS =**	st : 0.9
							c : 0.9
				H =	RP : 1		
						BE =	be : 1
					SYS : 1		
					LCC : 0.5		
						LCC =	ulc : 0.9
					A : 0.5		tlc : 0.9
					C : 0.5		slc : 0.3
					G : 0.5		
					SP : 0.2	**RP**	r = 1
				INT =	A 0.5	**A =**	ad : 0.9
					G : 1		as : 0.7
					C : 1		
					HR : 0.2	**G =**	gp : 0.9
							spe : 0.5
						C =	tc : 0.9
							af : 0.9
							t : 0.5
							mc : 0.7

Table 6.4: Weighting factors between DfD aspects and other nodes of the model

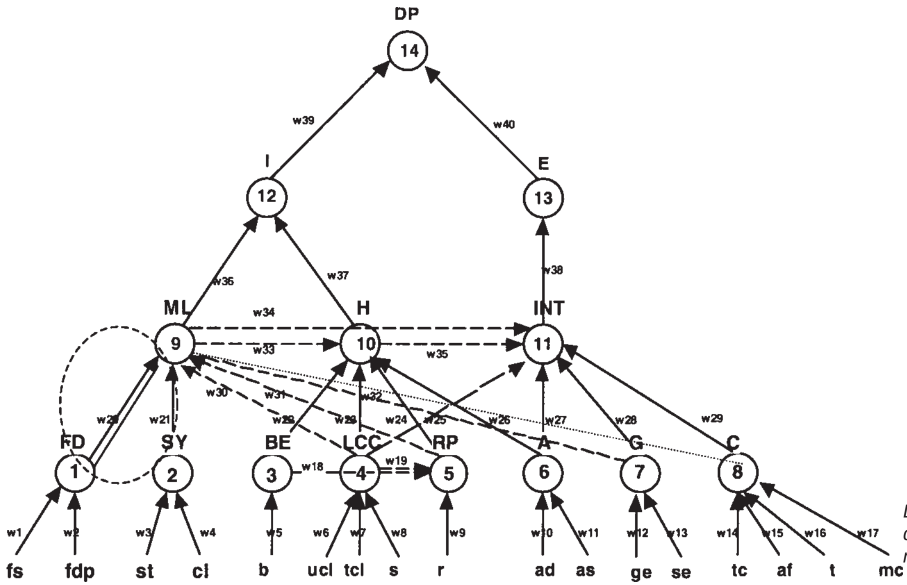


Diagram 6.1: Graphical representation of dependence between the evaluation nods of the model.

is given by functional decomposition, while the lowest is connection (See the table 6.4). If there is knowledge about functional decomposition and systematisation, different functions cannot be identified in independent elements, regardless of the type of connection. The design domain, which predominantly influences the exchangeability of components, is physical decomposition. Physical decomposition is defined as the function of assembly direction (A), geometry of product edge, type of connection, and relational pattern. However, the biggest influence is provided by the type of connection and the lowest by relational pattern. If two elements are connected with chemical connection they cannot be exchanged, regardless of the type of hierarchy.

6.2 CHOOSING THE METHOD FOR THE KNOWLEDGE MODELLING

The input data for the model are collected based on the expert assessment of different factors, which has an impact on the transformation potential of structures. The final goal of the model is to represent all factors that have an impact on TC by a single number. A simplified basic model is shown below.

In the model each variable is represented with a node. Thus, nodes represent factors, which play a role in the determination of the TC.

As already stated, the model is in a multi-level form with respect to the arranged nodes. In this respect relations between nodes are in a feed-forward structure such that causality among various dependencies is maintained. This means that any node in the model can affect only nodes with higher ranks.
The relations between inputs and nodes have been defined by weights, which indicate the level of their influence on the final result. For example, it has been estimated that functional decomposition has a greater influence on material decomposition than does relational pattern. If there is knowledge about functional decomposition, then material levels cannot be identified and separated. The type of connection has a greater influence on physical decomposition than on assembly sequences. Relational pattern has a greater influence on technical decomposition than do geometry of connection, and so on. If all elements have relations with each other, one closed relational pattern is created that cannot be opened without involving demolition, even if geometry of component edges are open and linear. The weights among different factors are presented in Table 6.4.
The weighting factor is based on analysis of each aspect and its impact on the deconstruction potential of the structure. It has been graded from 0 (worst value) to 1 (best value).

The collected information of the building design properties and weights is concisely represented in the form of a matrix, which is called the knowledge matrix. Thus, the knowledge matrix represents the relations/dependencies between the nodes. (Diagram 6.2) This information has been graded from worst, good, to best. The knowledge model represents a set of linguistic variables.

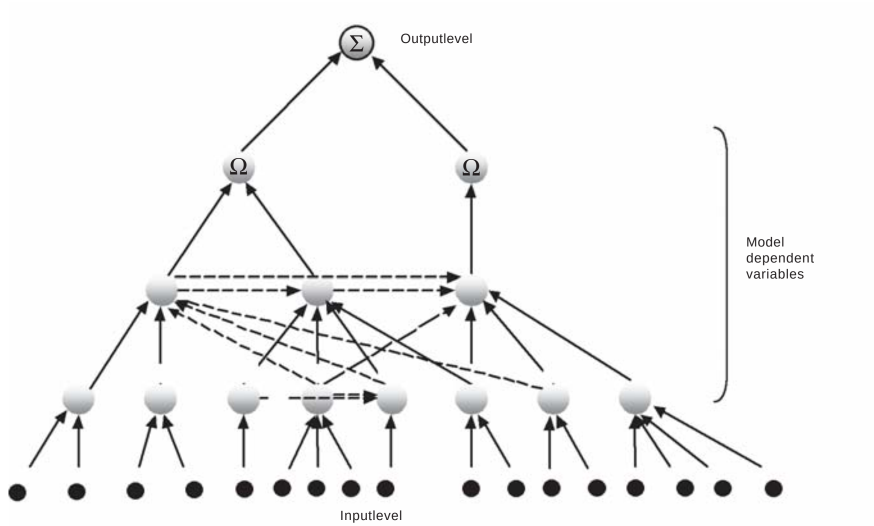


Diagram 6.2: Structure of the Knowledge Model

Therefore, one can say that the input data involved in this knowledge model is fuzzy in a sense that inputs represent categorical intervals rather than exact descriptions of state. Due to the nature of data, it becomes evident that tools that deal with vague and imprecise information (non-linear data) are essential for this knowledge model.

Traditional linear methods are unable to deal with non-linear data. This is due to the complexity of tasks and the relative lack of mathematical methods that deal with non-linear complexity.

To deal with fuzzy data sets, which are often called soft data by linear statistical models provide results in the form of a statistical model parameters with gross approximations. Contrary to this, the soft computing method deals with data without any parametric assumptions of the model. On the other hand, while attaching a membership function to each node in the model, the imprecision that is present at such ill-defined variables is taken care of. Each node is described by a fuzzy rule so that the node output is the firing strength of that rule.

Since building design is a highly knowledge-intensive process, most modern building design problems are either too complex or too ill defined to analyse using conventional methods. However, by defining the technical and functional requirements as a fuzzy set, one can perform inexact reasoning found during the conceptual or creative phase of the design process with optimal information routing and design decisions. A brief description of fuzzy logic is given below.

6.3 FUZZY LOGIC: AN OVERVIEW

Fuzzy set theory underlies fuzzy logic and fuzzy inference systems. Fuzzy logic explicitly aims to model the imprecise form of human reasoning and decision - making. These are essential to our ability to make rational decisions in situations of uncertainty. We encounter such imprecise cases often in real life situations. Human reasoning utilises imprecise propositions, and can also infer imprecise consequences. An example of such reasoning with respect to a moving car is: “if the speed is high, then reduce the gas”. This heuristic rule does not specify at exactly what point the speed becomes high, nor does it specify the amount by which the speed is reduced. Yet, it is still possible to apply this rule to satisfactorily control the speed of the car.

The fundamental concept of fuzzy logic is known as the linguistic variable. A linguistic variable is a variable that takes its values from spoken language. A linguistic variable can be described as:

- Qualitatively using an expression involving linguistic terms, and
- quantitatively using a corresponding membership function.

A linguistic term is useful for communicating concepts and knowledge between humans. In contrast, membership functions are useful for processing numeric input data.

Considering the car example above, such a variable can be assigned as high, medium, or low. Although these values do not have precise meanings, a certain distribution between zero and one can be defined and associated with these values. Thus, a speed of 40 km/h can be defined as medium and can be assigned the value 1. Any speed around this medium speed of 40 km/h is also medium, but the degree of being medium varies and is less than that assigned to 40 km/h. The more the speed differs from 40 km/h in any direction, the less the degree of association is. Such a distribution is commonly referred to as the membership function of the linguistic variables. These linguistic variables are called fuzzy variables.

The universe of discourse of a fuzzy variable is the finite input space for which the membership functions are defined. The shape of the membership functions is dependent on the attributes of the underlying concept, and can be represented by any normalised function. Each point in the input space has a degree of membership, which defines the degree to which that point belongs to a given fuzzy value. The membership value is conventionally shown by μ=[0., 1.]. Figure 6.04 represents the distributions of four linguistic values of speed using trapezoidal functions as fuzzy sets. These are the fuzzy membership functions and the universe of discourse is [0.0, 80 km/h] for this particular example.

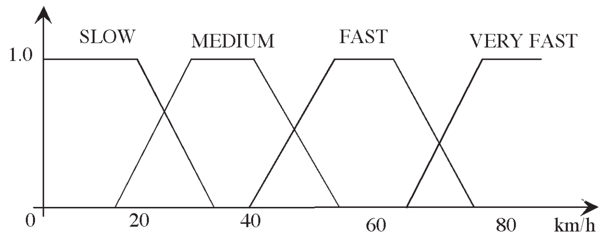


Figure 6.04: Typical fuzzy sets of speed

The concept of approximate reasoning plays an essential role in fuzzy systems. Typically, fuzzy reasoning is specified by a generalised modus ponens:
if a=A then b=B;
given a=A';
what is b? b=B'

All the values in the expressions above are represented by fuzzy membership functions and the implication b is derived using the fuzzy rule termed as *compositional rule of inference.* Conceptually, fuzzy systems are implicitly or explicitly rule-based systems, which comprise rules of the form:

$$IF\ \ a_1 = A_1^1\ \ AND\ \ a_2 = A_2^1\ \ AND\ .....\ \ THEN\ \ b = B_1$$
$$ALSO$$
$$IF\ \ a_1 = A_1^2\ \ AND\ \ a_2 = A_2^2\ \ AND\ .....\ \ THEN\ \ b = B_2$$
$$ALSO\ ....$$

where all variables and values are fuzzy.
One sees, that with fuzzy sets, a numerical value is classified into one or more linguistic labels. These labels may be discrete or continuous and the membership

functions represent the numerical strength of linguistic labels for the domain of classification. Since the membership functions can overlap, this results in a multi-value representation of knowledge. An input value intersects with one or more membership functions of the input classification and therefore it is attached to several linguistic labels.

6.4 DESCRIPTION OF THE KNOWLEDGE MODEL

In the sample basic model in Diagram 6.01, there are 14 main nodes playing a role in the determination of TC. Each node has sub-components represented by incoming arrows. In the model, each node corresponds to a rule, and with the combination of 14 nodes, TC is determined. The relations among main components are represented by relevant weight factors. Each weight is between 0 and 1 and represents the strength of the relation. This is an estimated value with its associated imprecision. Therefore, it is conveniently represented as a fuzzy variable characterised by a membership function. The membership functions used in this work are in the form of Gaussian functions. Thus, a membership function μ is given by

$$\mu(x_p) = \exp(-(x_p - w_{ij})^2 / 2\sigma^2$$

Where w_{ij} and s are the mean and variance of the Gaussian, respectively. A fuzzy “AND” is performed by arithmetic multiplication. The mean of each Gaussian is characterised by the weight factors of the knowledge model. For x_p=$w_{ij,}$ we obtain m(x_p)=1 so that, the knowledge model verifies the TC for the standard inputs forming the model. In this case, the membership functions take the maximum values indicating that the values of the components have their best representational values. Consequently, the representative knowledge model is formed.

The model having been determined can be used for the assessment of TC for different inputs. For these inputs the membership functions take their respective values and determine the associated TC. The knowledge model first calculates the ideal case regarding the calculated TC.
The ideal case is used as a standard case $TC_{s.}$ Since the knowledge model has

well defined nodes that define the ideal TC, say TC_s, any deviation from these values, i.e., for each test inputs will diminish the TC with respect to TC_s, to some extent.

In the knowledge model the TC has been normalised by TC_s so that the transformation capacity can be obtained as a ratio of TC/TC_s. This ratio is interpreted as the ability for transformation to occur.

For standard inputs, transformation is unity since the model is based on these inputs, and on well defined relations between nodes.

For test inputs, the assessment for each output node is determined by the membership functions. Fuzziness plays a major role in obtaining the final result.

6.5 PROTOCOL FOR THE ASSESSMENT OF TRANSFORMATION CAPACITY

The proposed assessment method should give answers to three questions:

1. Does a functional composition correspond to the desired transformational requirements?
2. Does a technical composition correspond to the desired transformational requirements?
3. Does a physical composition correspond to desired transformational requirements?

The answers to these questions indicate the disassembly potential of the particular solution, with respect to specific transformation requirements.

However, buildings and systems can be evaluated only after basic performance conditions regarding transformation have been set.

Taking this into account, assessment of TC can be split up into the following phases:

1. Defending the systems boundaries: establishing clear performance criteria for transformation.
2. Data Collection: analysis of the technical composition of configuration.
3. Evaluation: Building of the process tree, normalisation, characterisation, and weighing of the different categories. As a result of these calculations, a graph

with the impacts of the different aspects on transformation is presented. With a developed knowledge model for the assessment of TC, these different categories can be combined into one figure. Finally, it is possible to indicate the aspects that should be improved to achieve better performance.

4. Improvement assessment. As a result of the evaluation, parts of the configuration have greater impacts on total TC than on others. To improve the total TC, improvements can be made to those parts of the product or construction that have the greatest impact.

6.6 CASE STUDY

In the previous text, description of a knowledge model for assessment of TC is given. The model is generic in a sense that it can be used to assess disassembly characteristic of any structure (building, system, or component structure).

For the experimental investigation of the model, Project XX was chosen as a case study. Project XX is an experimental office building designed from the outset for sustainability (see Chapter 5). As mentioned in the previous text, two assessments have been done regarding the XX building, according to two performance requirements. One assessment indicates the disassembly potential of the total structure (Table 6.5 and 6.06), while another assessment indicates the disassembly potential during replacement of the façade system (Table 6.7 and 6.8). The table 6.5 shows knowledge matrices regarding the first assessment, with corresponding inputs and weights. Output matrix is presented in table 6.6. This gives a measure of each node within the knowledge model. Input data has been collected based on evaluation of each design aspect. This is discussed in Chapter 5.

TEST CASE
XX Building

	node	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Input weights from 0 to the 1st level of KM	1	0.9	0.7	0	0	0	0	0	0	0	0	0	0	0	0
	2	0.9	0.9	0	0	0	0	0	0	0	0	0	0	0	0
	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0.9	0.9	0.3	0	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	0.9	0.7	0	0	0	0	0	0	0	0	0	0	0	0
	7	0.9	0.5	0	0	0	0	0	0	0	0	0	0	0	0
	8	0.9	0.9	0.5	0.7	0	0	0	0	0	0	0	0	0	0
	node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Weights between the nods	9	0.9	0.9	0	0.4	0.3	0	0	0.3	0	0	0	0	0	0
	10	0	0.4	0.9		0.9	0.7		0.3	0	0	0	0	0	0
	11	0	0	0	0.9	0	0.7	0.7	0.9	0.2	0.2	0	0	0	0
	12	0	0	0	0	0	0	0	0	0.9	0.9	0	0	0	0
	13	0	0	0.4	0	0.2	0	0	0	0	0	0.9	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0.9	0.9	0

Table 6.5: A knowledge matrix with corresponding inputs and weights regarding the assessment of the XX building system.

Input /standard (ideal) case

node				
1	1	1	0	0
2	1	1	0	0
3	1	0	0	0
4	1	1	1	0
5	1	0	0	0
6	1	1	0	0
7	1	1	0	0
8	1	1	1	1

Input/test case XX building

node				
1	1	0.65	0	0
2	0.8	1	0	0
3	1	0	0	0
4	0.8	0.78	0.85	0
5	1	0	0	0
6	0.86	0.63	0	0
7	1	0.96	0	0

Knowledge model nods	outputs	node nr.
functional decomposition	8,29E-01	1
systematisation	9,04E-01	2
base element	1	3
LCC	7,94E-01	4
relational pattern	1	5
assembly	7,72E-01	6
geometry	9,99E-01	7
connection	4,54E-01	8
material levels	8,78E-01	9
hierarchy	9,22E-01	10
interfaces	5,47E-01	11
Independence	9,67E-01	12
exchangeability	7,17E-01	13

Table 6.6 Left: The matrix represents input data on the 0 level with respect to the performance of the XX building. Right: Output of the model is a calculation per each node within the model - total 14 nodes (seeTable 6.01b).

Table 6.7: The standard knowledge matrix, where the weights between the input and first level of the model are defined, as well as the weights between all nodes that have influence on the final TC.

TEST CASE
XX façade system

	node	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Input weights from 0 to the 1st level of KM	1	0,9	0,7	0	0	0	0	0	0	0	0	0	0	0	0
	2	0,9	0,9	0	0	0	0	0	0	0	0	0	0	0	0
	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0,9	0,9	0,3	0	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	0,9	0,7	0	0	0	0	0	0	0	0	0	0	0	0
	7	0,9	0,5	0	0	0	0	0	0	0	0	0	0	0	0
	8	0,9	0,9	0,5	0,7	0	0	0	0	0	0	0	0	0	0
	node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Weights between the nods	9	0,9	0,9	0	0,4	0,3	0	0	0,3	0	0	0	0	0	0
	10	0	0,4	0,9	0	0,9	0,7	0	0,3	0	0	0	0	0	0
	11	0	0	0	0,9	0	0,7	0,7	0,9	0,2	0,2	0	0	0	0
	12	0	0	0	0	0	0	0	0	0,9	0,9	0	0	0	0
	13	0	0	0,4	0	0,2	0	0	0	0	0	0,9	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0,9	0,9	0

Table 6.8 Left: The matrix represents input data on the 0 level with respect to the performance of the XX facade. Right: Output of the model is a calculation per each node within the model - total 14 nodes (seeTable 6.01b). .

Input /standard (ideal) case

node				
1	1	1	0	0
2	1	1	0	0
3	1	0	0	0
4	1	1	1	0
5	1	0	0	0
6	1	1	0	0
7	1	1	0	0
8	1	1	1	1

input/test case XX façade

node				
1	1	1	0	0
2	1	1	0	0
3	0,4	0	0	0
4	1	1	1	0
5	0,1	0	0	0
6	0,1	1	0	0
7	0,1	0,5	0	0
8	0,4	0,1	0,5	0,6

Knowledge model nods	outputs	node nr.
functional decomposition	8,29E-01	1
systematisation	9,04E-01	2
base element	1	3
LCC	7,94E-01	4
relational pattern	1	5
assembly	7,72E-01	6
geometry	9,99E-01	7
connection	4,54E-01	8
material levels	8,78E-01	9
hierarchy	9,22E-01	10
interfaces	5,47E-01	11
Independence	9,67E-01	12
exchangeability	7,17E-01	13

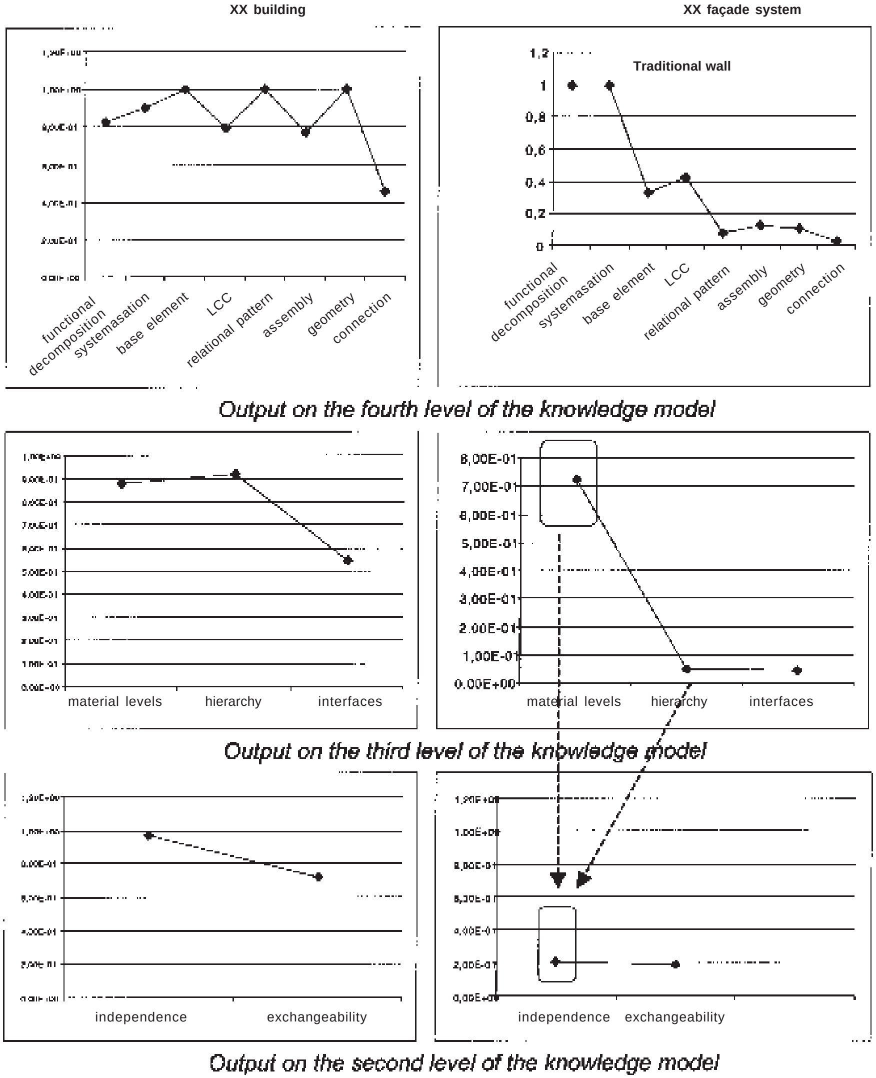
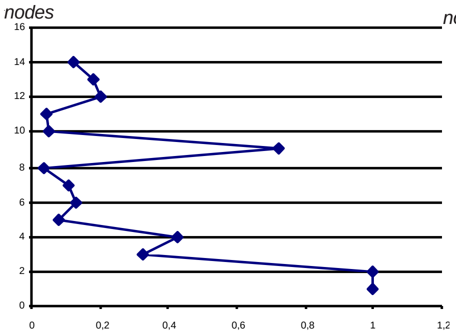


Figure 6.05: Outputs of the Knowledge Model calculations on the second, third, and fourth level.

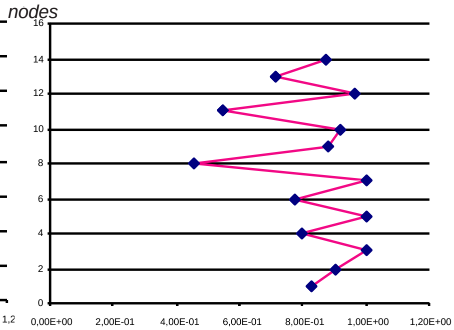
Although the knowledge model (regarding the xx façade) calculates a relatively high index for material level specification (see outputs on the third level), the independence and exchangeability factors are very low (see outputs on the second level in Figure 6.05). This is because besides material levels, the hierarchy also has a big influence on the determination of the independence of elements. This can be clearly seen in diagrams representing calculations of TC regarding the XX façade (Figure 6.06). As already discussed, these influences are taken care of by defining the weights within the model .

The figure 6.06 shows the calculation of all factors that play a role in defining the transformation capacity. Although there are a number of factors in left diagram of the figure (representing the XX façade system) which range above 0,2 points the final calculation of TC is TC=0,12. (See Figure 6.07) The aspects that contribute to such a low value are primarily the relational pattern between components, assembly direction geometry of product type, and connections.

Figure 6.06 left: The final calculation of the design for disassembly aspects of the XX building at the end of its life cycle and;
right: The final calculation of the design for disassembly aspects of the XX façade during operation of the building.



TC value in each node of the model (xx facade). Node 14 = final TC value



TC value in each node of the model (xx building). Node 14 = final TC value

The results of the assessment of disassembly potential for the XX building (Figure 6.06 left) indicate that the key aspects of design for deconstruction such as material systematisation for deconstruction, functional decomposition, base element specification, open hierarchy did play a role during the design process (results are closer to 0.9).

However, the design of interfaces that is an important element of deconstruction, can be improved by more efficient DfD (Figure 6.05 second level).

For example, the connection between primary and secondary beams can be characterised as an “ internal accessory connection ” in which 30cm long pins are inserted to connect two beams. Removal of the pins causes damage to the beam. The connection between concrete floor and finishing is a direct chemical connection that leaves no space for disassembly. The same applies to the wall finishing.

All other connections between load bearing frame and façade, roof, wall subsystem, and installations are dismountable (see case study Chapter 5). For this reason when calculating the disassembly potential of detailing of the XX building for disassembly is Int = 0.753 or 75%, suitability of material systematisation SYS=0.89 pr 89%, and suitability of hierarchy H=9.31 or 93%.
Accordingly, the total Disassembly Potential of XX building structure D=0.87 or 87% (Figures 6.07).

The disassembly potential calculated for XX façade system (suitability of the structure for replaceability of facade panels) is much less than the disassembly potential of the first scenario (Figure 6.07). Details that are not suitable for exchangeability of façade panels cause such a result (see results of calculation per node presented in the net graph figure 6.07 right).
The aspects that should be improved for more efficient disassembly potential are: assembly direction, geometry of component edge, type, and morphology of connection.

Another conclusion that can be drawn out of this case study is that even though the building can be defined as dismountable at the and of its life cycle, this does not mean that its individual components can be disassembled during the operational phase of the building. This is the case with the XX facade system.

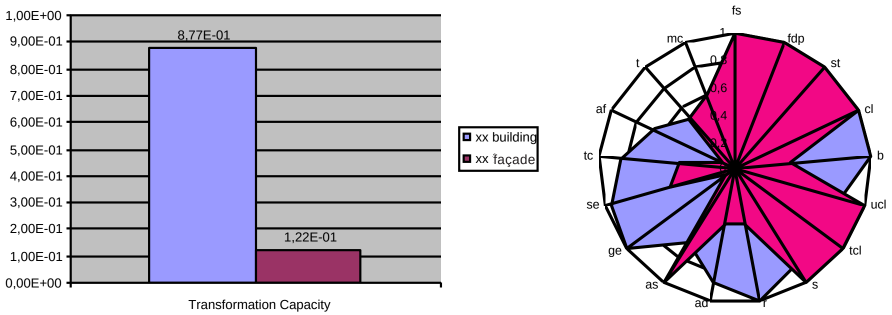


Figure 6.07 left: The final calculation of the transformation capacity of the XX building at the end of its life cycle; right shows the final calculation of the transformation capacity of the XX façade during operation of the building.

High Transformation capacity = low negative impact on the environment

6.6.1 Case study SMR - Evaluation

To test the model, it has been decided to compare three wall systems regarding exactly the same performance requirements.

The first wall: Traditional block walls with integrated installations.

The second wall: Traditional block wall with independent zone for electrical installations (SMR). This zone is inserted into the wall and provides separation between the partitioning wall and electrical installations.

The third wall: Demountable panel wall. Wooden panes are mounted on steel studs. The separate zone for electricity is placed in lower zone of the wall. (Figure 6.08)

wall type 1

wall type 2

wall type 3

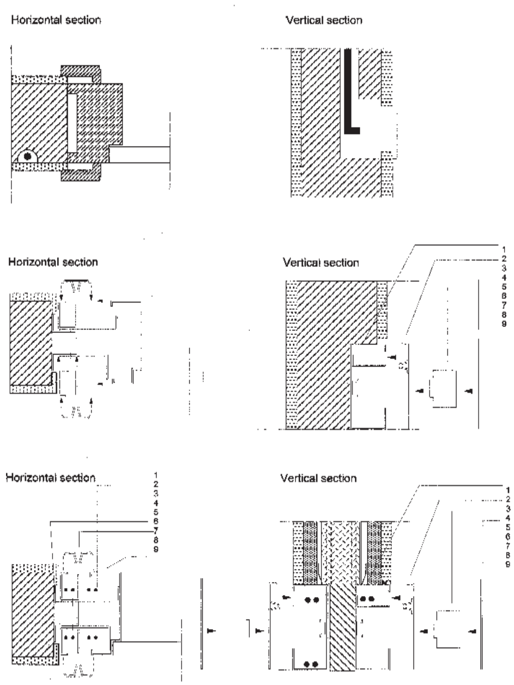


Figure 6.08: three types of wall systems:
wall type 1- conventional wall
Wall type 2 – conventional wall with separated zone for electrical components
Wall type 3- flexible wall system with demountable components

Defending the systems boundaries

The first step has to do with setting up a framework for the evaluation.

In other words, performance criteria is evaluated regarding the transformation capacity of three wall systems.

In this case the internal partitioning of conventional dwellings has been taken as a use strategy where the design life of the building is 75 years. The frequency of internal partitioning (use life cycle) has been adopted from market research of the Housing Corporation in Amsterdam. (Table 6.9) This research indicates that inhabitants put internal flexibility of their apartments as an absolute priority, especially when it comes to the resizing of rooms (see Chapter 2). At the building level internal flexibility (or optimal spatial flexibility) means that the partitioning of walls can be replaced in order to resize the space. This use strategy means that partitioning elements, outlets and electrical components need to be reusable at the system level.

The specification of the building components according to their use expectancy is shown in the table 6.9.

Table 6.9: durability of materials and their performance expectencies;
** Reference from the “Piramide wining” Het OOsten*
*** Reference from theSBR report 1998 “Levensduur van Bouwprodukten (praktijkwaarden)*

	building level	system level	durability of material	performance expectancies
fixed	**loadbering**	construction	75-100 years**	75-100 years
	accessories	lift	25 years**	
		trap	75-100**	75-100 years
	envelope	façade	20-75 years**	20-50 years
		roof	15-50**	
	core installations -	standlijding	50**	50
		waterlijdingen	50**	50
	main network	rookgaskanaal	30-50**	50
		ventilation kanaal	30-50**	50
		energievoorzining-centrale	30-50**	50
flexible	**distribution of**	watterlijdingen naar kk,bk,t	25**	30*
	installations	gasleidingen	45**	30*
	distribution network	electrainstallaties(wandgot)	25**	30*
		electrainstallaties(bedrading)	40**	30*
	separation system	metaldelen	50**	
	walls	gips platen	20**	all together 8-10*
		kozijnen	50**	
	finishing	tegelwerk	75 years**	2_8 *
		stuckwerk	30**	2_8 *
		houten vloer	40**	2_8 *
		anhidriet flour	60**	2_8 *
		stein flour	75**	2_8 *
	end appliances	keuken element	20**	2_8
		bad	20**	2_8
		toilet,....	20**	2_8

The comparison of the use life cycle and technical life cycle of all building components in existing housing projects has been done according to this flexibility scenario, which identifies partitioning walls, doors, and electricity components as disassembly sensitive parts. The life cycle coordination analysis (Figures 6.09 and 6.10) shows that partitioning elements have a reuse potential of seven times, while electricity components have a reuse potential of four times. Such reuse potential can provide material reduction of 80% during the operational phase, if elements are reusable.

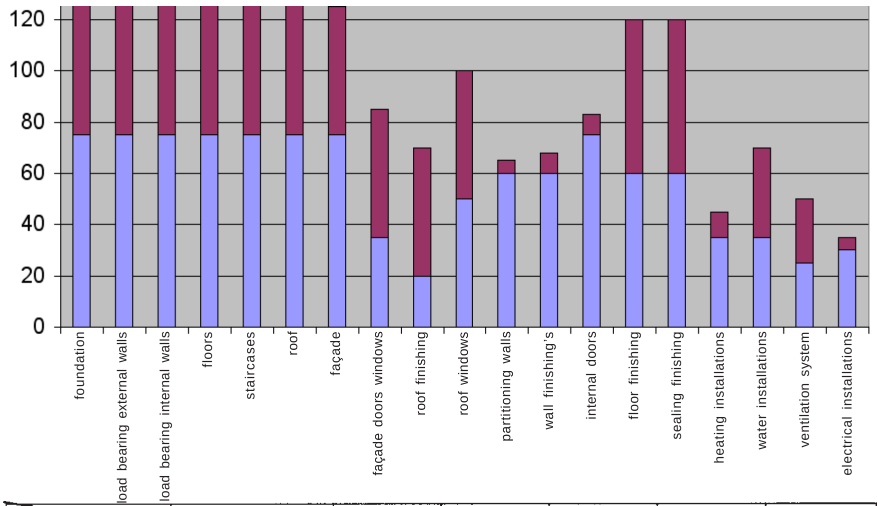


Figure 6.09: comparison of use and technical life cycle of building components within one conventional housing project.

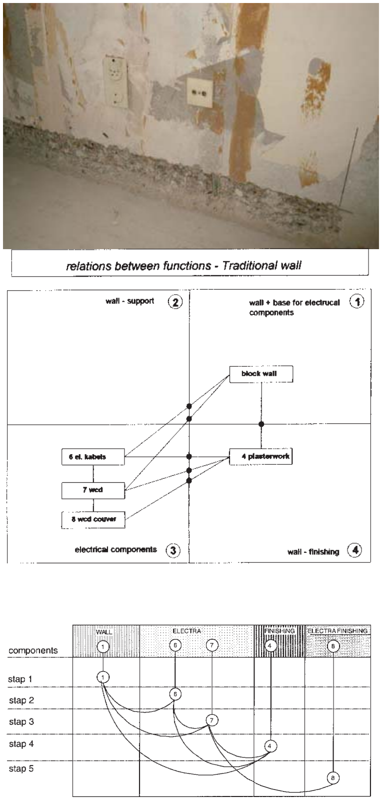
Main functions of building elements / Use scenarios		Optimal functional flexibility	**Optimal spatial flexibility**	Maximal spatial flexibility	Maximal functional flexibility	Maximal flexibility
	Technical durability	Use durability	Use durability	Use durability	Use durability	Use durability
Load bearing	75 years	75 year	75 year	75 year	75 year	75 year
V. Communication	75 years	75 year	75 year	5 year	5 year	5 year
Cladding	50 years	50 year	50 year	5 year	50 year	5 year
Servicing Core distribution	30 years	30 year	30 year	5-30 year	5-30 year	5 year
Gas distribution sub net	30 years	5-8 years	30 year	5-8 years	5-8 years	5-8 years
Water distribution sub net	30 years	5-8 years	30 year	30 year	5-8 years	5-8 years
air distribution sub net	30 years	5-8 years	30 year	30 year	5-8 years	5-8 years
Electrical distribution sub net	30 years	5-8 years	**5-8 years**	5-8 years	5-8 years	5-8 years
Partitioning elements	75 years	5-8 year	**5-8 year**	5-8 year	5-8 year	5-8 year
Outlets	20 years	2-5 year	**2-5 year**	2-5 year	2-5 year	2-5 year

Figure 6.10: comparison of the use and technical life cycle of building components within five use scenarios.

According to this the TC of three partitioning systems has been calculated in relation to independence and exchangeability of partitioning elements and electricity elements.

Data Collection – Analyses of systems configurations

The configuration of three types of walls have been analysed in order to provide the input data for the knowledge matrix. Finally, TC has been calculated by the use of the knowledge model discussed in this chapter. The LCA of the three wall systems has been assessed as well. The goal of this case study was also to draw a relation between TC and environmental efficiency. Figures 6.11 left and 6.11 right present conventional and flexible wall types. Data regarding disassembly potential of these two wall types are shown in Tables 6.10 and 6.11.



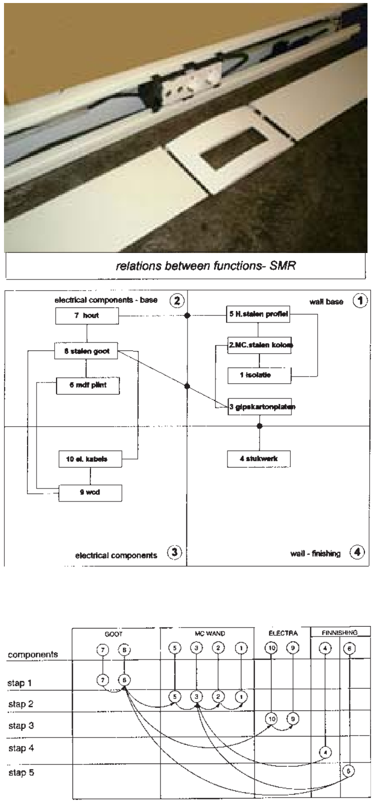


Figure 6.11 left: Figure shows functional relations between four functional groups within conventional partitioning wall system (supporting, servicing electricity and finishing) and their assembly relations

Figure right shows functional relations between four functional groups within flexible partitioning wall system (supporting, servicing electricity and finishing) and their assembly relations.

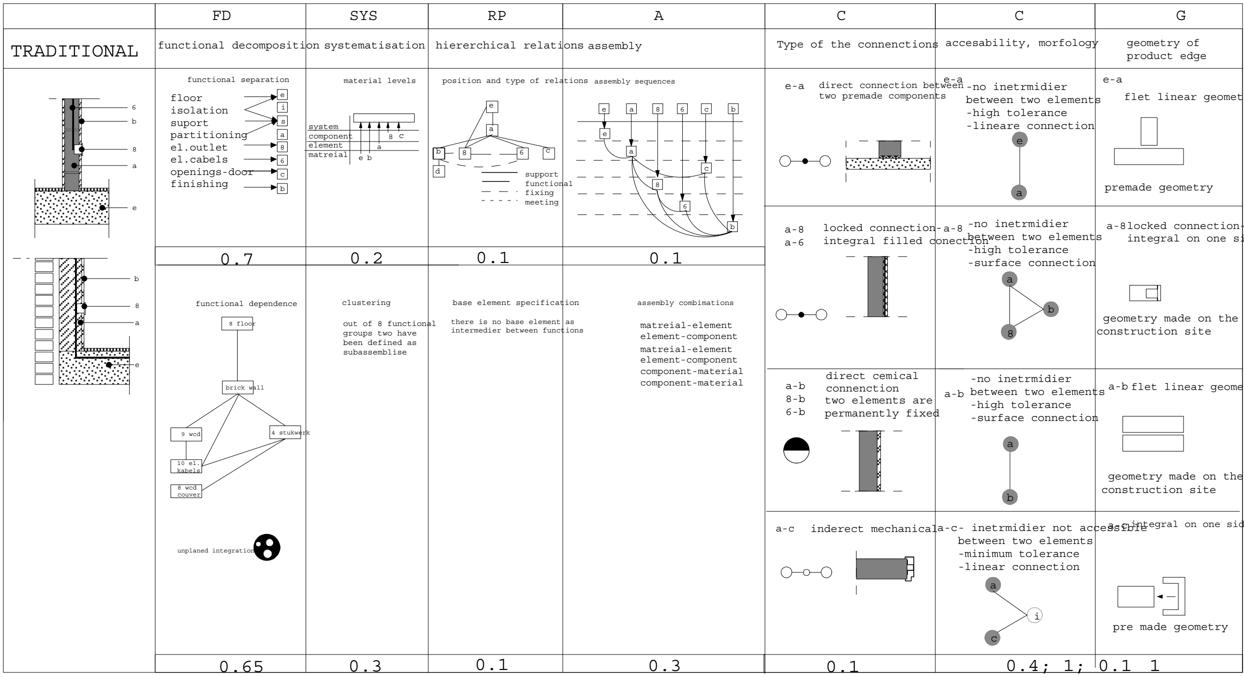


Table 6.10: Conventional block wall: analyses of disassembly aspects

Table 6.10 illustrates the disassembly characteristics of configuration of traditional wall.

Some characteristics that have a major impact on the disassembly potential of this configuration are:

- Functional dependency between partitioning wall and electrical installations,
- sequential assembly sequences,
- lack of systematisation of components,
- a high level of dependency created by the greater number of relations between all components,
- lack of proper base element for the configuration, and
- use of chemical connections.

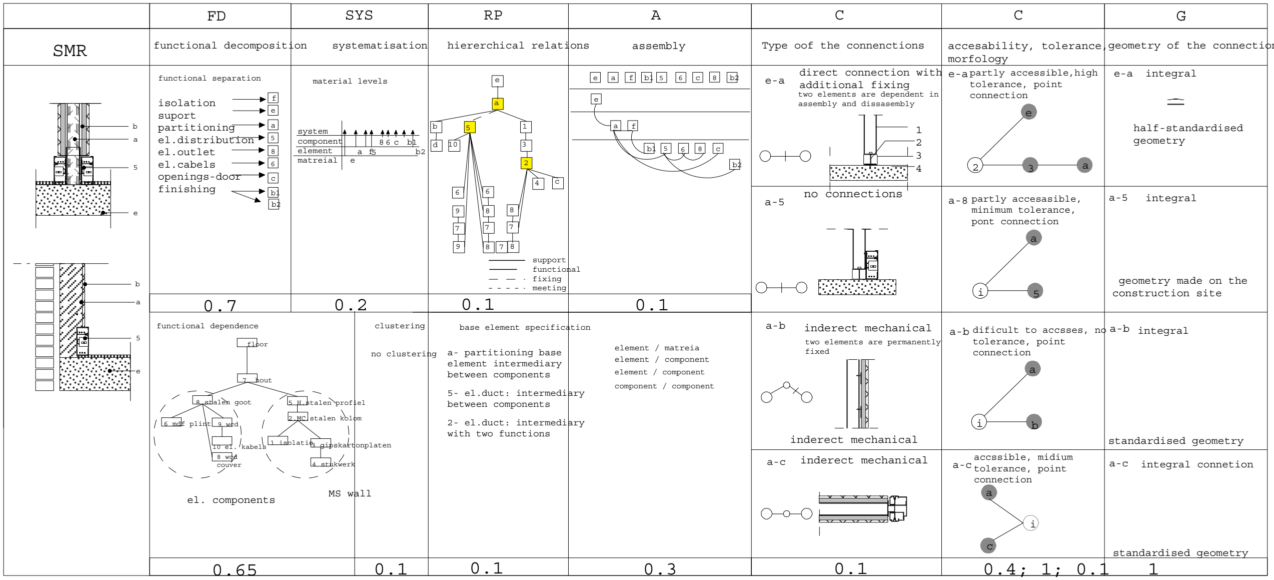


Table 6.11. Flexible wall: analyses of disassembly aspects

The table 6.11 illustrates the disassembly characteristics of configuration of flexible wall system (SMR).

The aspects that have major impact on disassembly poptential of this configuration are:

- High level of independence between assembly groups that have different functions and life cycles,
- use of dismountable connections between the main assembly groups: support, partitioning wall, electricity, and door,
- use of intermediaries between partitioning walls and electrical installations, as well as between structural floors and partition walls,
- application of parallel assembly sequences,
- use of parts with integral self-locking features.

Evaluation

The assessment of TC of wall systems has been done through analysis of the main aspects of deconstruction. Evaluation of these aspects is presented in the table 6.12, 6.13 and 6.14, 6.15. The influence of each aspect on the transformation is assessed proportionally, and finally normalisation has been performed.

Table 6.12: The standard knowledge matrix, where the weights between the input and first level of the model are defined, as well as the weights between all nodes that have influence on the final TC.

TEST CASE
SMR wall

	node	0	0	0	0	0	0	0	0	0	0	0	0	0	0
input weights first level of the KM	1	0.9	0.7	0	0	0	0	0	0	0	0	0	0	0	0
	2	0.9	0.9	0	0	0	0	0	0	0	0	0	0	0	0
	3	1		0	0	0	0	0	0	0	0	0	0	0	0
	4	0.9	0.9	0.3	0	0	0	0	0	0	0	0	0	0	0
	5	1		0	0	0	0	0	0	0	0	0	0	0	0
	6	0.9	0.7	0	0	0	0	0	0	0	0	0	0	0	0
	7	0.9	0.5	0	0	0	0	0	0	0	0	0	0	0	0
	8	0.9	0.9	0.5	0.7	0	0	0	0	0	0	0	0	0	0
weights between the nods	**node**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
	9	0.9	0.9	0	0.4	0.3	0	0	0.3	0	0	0	0	0	0
	10	0	0.4	0.9	0	0.9	0.7	0	0.3	0	0	0	0	0	0
	11	0	0	0	0.9	0	0.7	0.7	0.9	0.2	0.2	0	0	0	0
	12	0	0	0	0	0	0	0	0	0.9	0.9	0	0	0	0
	13	0	0	0.4	0	0.2	0	0	0	0	0	0.9	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0.9	0.9	0

Table 6.13 Left: The matrix represents input data on the 0 level with respect to the performance of the SMR wall. Right: Output of the model is a calculation per each node within the model - total 14 nodes (seeTable 6.01b). .

Input /standard (ideal) case

node				
1	1	1	0	0
2	1	1	0	0
3	1	0	0	0
4	1	1	1	0
5	1	0	0	0
6	1	1	0	0
7	1	1	0	0
8	1	1	1	1

input/test case wall traditional

node				
1	0.7	0.65	0	0
2	0.2	0.1	0	0
3	0.1	0	0	0
4	1	0.6	0.67	0
5	0.1	0	0	0
6	0.1	0.3	0	0
7	1	0.4	0	0
8	0.1	0.4	1	0.1

Knowladge model nods	outputs	node nr.
functional decomposition	8,71E-01	1
systematisation	1	2
base element	6,07E-01	3
LCC	9,39E-01	4
relational pattern	8,82E-01	5
assembly	8,95E-01	6
geometry	9,75E-01	7
connection	5,41E-01	8
material levels	9,34E-01	9
hyerarchy	7,25E-01	10
interfaces	6,94E-01	11
Independece	8,78E-01	12
exchangeability	8,17E-01	13
Transformation Capacity	9,25E-01	14

TEST CASE
traditional partitioning wall

	node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
input weights first level of the KM	1	0.9	0.7	0	0	0	0	0	0	0	0	0	0	0	0
	2	0.9	0.9	0	0	0	0	0	0	0	0	0	0	0	0
	3	1		0	0	0	0	0	0	0	0	0	0	0	0
	4	0.9	0.9	0.3	0	0	0	0	0	0	0	0	0	0	0
	5	1		0	0	0	0	0	0	0	0	0	0	0	0
	6	0.9	0.7	0	0	0	0	0	0	0	0	0	0	0	0
	7	0.9	0.5	0	0	0	0	0	0	0	0	0	0	0	0
	8	0.9	0.9	0.5	0.7	0	0	0	0	0	0	0	0	0	0
weights between the nods	node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	9	0.9	0.9	0	0.4	0.3	0	0	0.3	0	0	0	0	0	0
	10	0	0.4	0.9	0	0.9	0.7	0	0.3	0	0	0	0	0	0
	11	0	0	0	0.9	0	0.7	0.7	0.9	0.2	0.2	0	0	0	0
	12	0	0	0	0	0	0	0	0	0.9	0.9	0	0	0	0
	13	0	0	0.4	0	0.2	0	0	0	0	0	0.9	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0.9	0.9	0

Table 6.14: The standard knowledge matrix, where the weights between the input and first level of the model are defined, as well as the weights between all nodes that have influence on the final TC.

Input /standard case

node				
1	1	1	0	0
2	1	1	0	0
3	1	0	0	0
4	1	1	1	0
5	1	0	0	0
6	1	1	0	0
7	1	1	0	0
8	1	1	1	1

input/test case SMR

node				
1	1	0.7	0	0
2	1	1	0	0
3	0.6	0	0	0
4	1	0.85	0.85	0
5	0.8	0	0	0
6	0.86	0.8	0	0
7	0.9	1	0	0
8	0.83	0.8	0.5	0.6

Knowladge model nods	outputs	node nr.
functional decomposition	6,60E-01	1
systematisation	2,55E-02	2
base element	7,96E-02	3
LCC	8,32E-02	4
relational pattern	7,96E-02	5
assembly	6,08E-02	6
geometry	7,55E-01	7
connection	1,50E-02	8
material levels	9,81E-02	9
hyerarchy	1,68E-02	10
interfaces	1,83E-02	11
Independece	5,59E-02	12
exchangeability	1,50E-01	13
Transformation Capacity	7,31E-02	14

Table 6.15 Left: The matrix represents input data on the 0 level with respect to the performance of the traditional partitioning wall. Right: Output of the model is a calculation per each node within the model - total 14 nodes (seeTable 6.01b). .

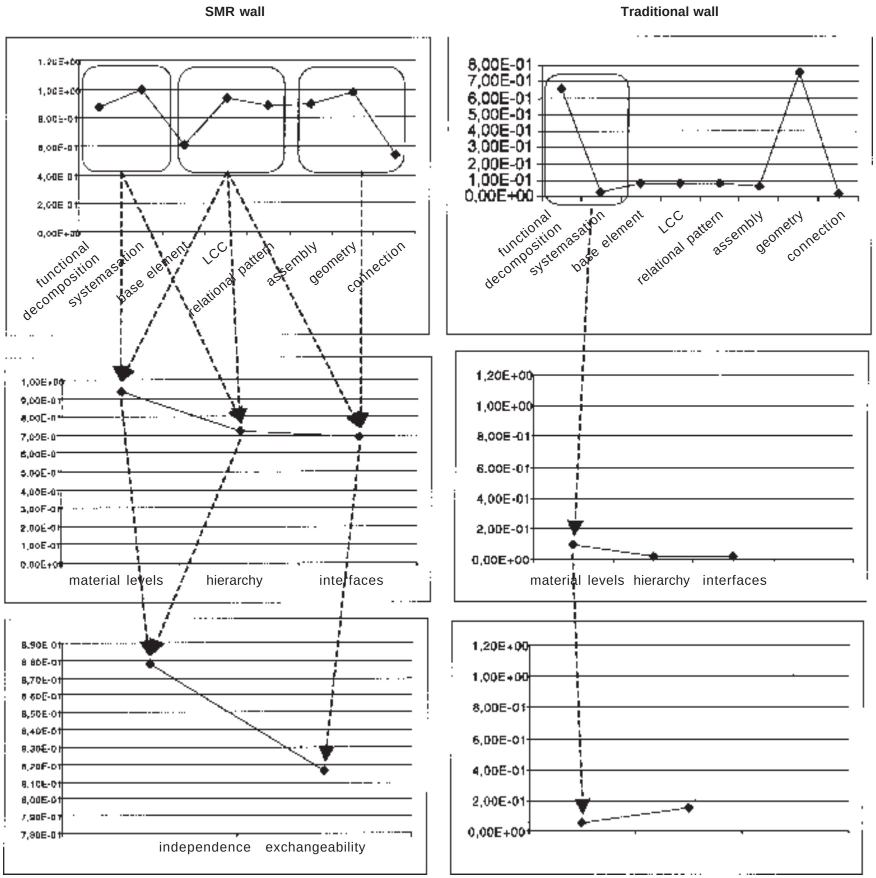


Figure 6.12: figure left shows the result of the calculation of transformation capacity of two wall systems; figure right shows all indicators of transformation for the two wall systems.

Although the functional decomposition of a traditional wall has a relatively high score, the fact that there is no systematisation involved (such that clusters could be identified and disassembled), material decomposition is calculated to be very low. Consequently, the independence of components is very low. See figure above right.

The net graph in figure 6.13 right shows the assessment of all factors that determine transformation capacity, while the figure 6.13 left represents the results of calculation, where different influences of disassembly factors have been built into the calculation of the model. This calculation is finally presented with one number representing TC of systems configurations. (Figure 6.13 left)

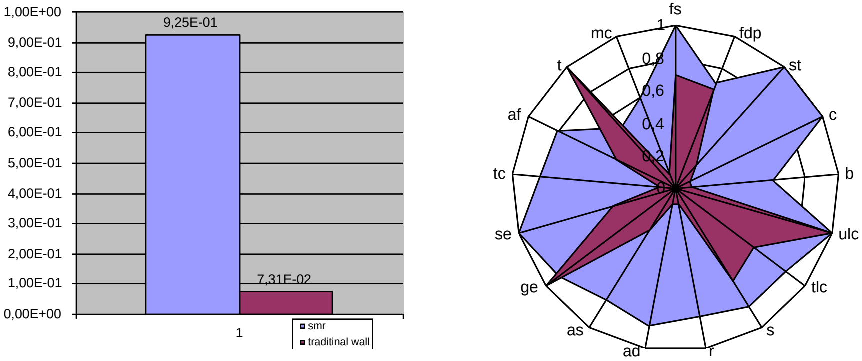


Figure 6.13 left shows the final calculation of the transformation capacity of the two wall systems Figure right shows net graph with calculated design for disassembly aspects

Figure 6.14 left and right show the hierarchical order from negative to positive influence of disassembly aspects of the final result. The aspects that are on top of the table should be improved to achieve a better transformation performance of the evaluated systems.

-	1	connections
	2	base element
	3	relational patern
	4	assembly direction
	5	geometry
	6	lcc
	7	functional decom
+	8	systematisation

Hierarchy of aspects – SMR system

-	1	systematisation
	2	lcc
	3	connections
	4	base element
	5	relational patern
	6	assembly direction
	7	functional decom
+	8	geometry

Hierarchy of aspects traditional wall

Figure 6.14 left shoves a priority list for the improvement of transformation capacity of the SMR system
Figure 6.14 right shows a priority list for the improvement of the transformation capacity of the traditional block wall.

6.7 ENVIRONMENTAL BENEFITS

The hypotheses of this research is that greater TC results in lower environmental impact, since high transformation ability means that buildings can be adopted to the new requirements and their components, and materials can be replaced, reused, reconfigured, and recycled.

To illustrate the environmental impact of the above definitions,the environmental impact and TC of three types of partitioning wall systems have been compared.

The environmental impact of each system has been calculated, taking into account the number of changing sequences of the wall, door, and electrical components. These result from a lifecycle co-ordination matrix and reuse and recycling characteristics of system components that result from analysis of configurations. Separate calculations are made for wall and door sections. The result of this comparison is shown in Figure 6.15. These data have been calculated with the program SimaPro, using the calculation method EcoIndicator 95. This is commonly used software for making life cycle assessments of materials.

Calculations are made for a period of 75 years. During these 75 years all walls have been replaced (or rebuilt) seven times. Since such assessments are not atomised in existing LCA models, the transformation process has been defined for each type of wall according to which LCA has been made. This assessment also added a number of changing sequences for each component.

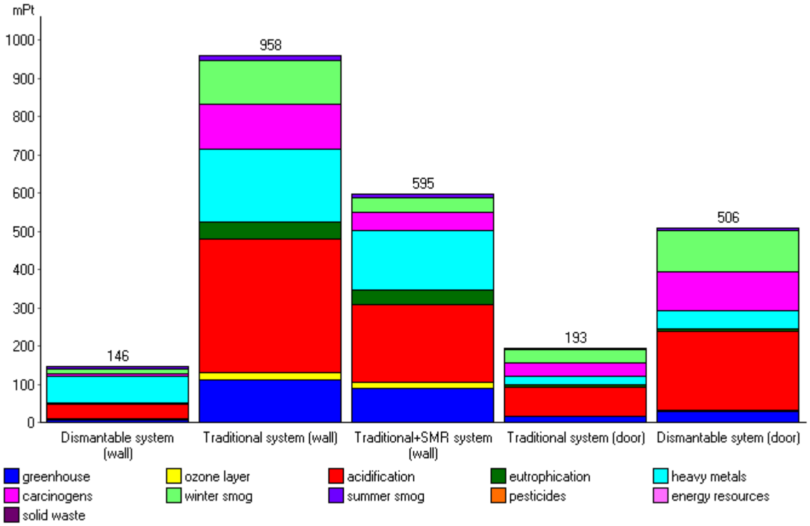


Figure 6.15: LCA of three types of wall Comparing product stages Method: Eco-Indicator 95/Europe/Single score

The figure 6.15 presents the life cycle assessments of each wall system, taking into account their transformation and reuse characteristics over 75 years.
If the total number of replacements is fewer, environmental impacts change. The diagram below represents the relation between environmental impact and changing sequences. In this case the changing sequence of the wall is 10 years. For a technical life cycle of 75 years the wall can be reused seven times. This case illustrates that application of flexible wall for the chosen flexibility strategy is environmentally feasible already after its second replacement. Therefore, already after the second replacement the environmental impact of a flexible wall are lower than the environmental impact of a traditional wall. (Diagram 6.3)The more changing sequences there are, the lower the environmental impact is.

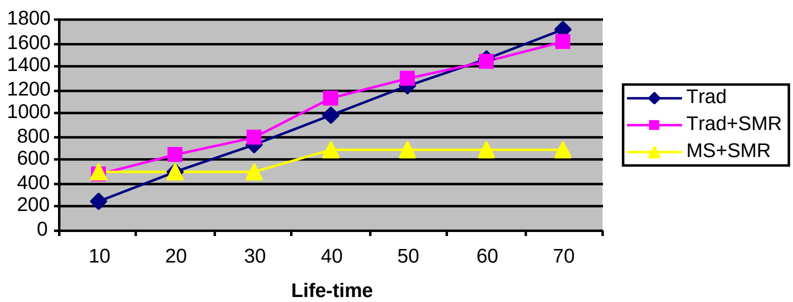


Diagram 6.3: Environmental impact of 3 types of wall with a use phase of 10 years within the building whose service life is 75 years

es.
Furthermore, it is important to notice that this assessment is based on the assumption that 40% of steel production is recycled and 60% of steel production is made of raw material. There are calculations within the steel industry that the 40/60 relation can be changed to 60/40 very soon. In this case the environmental impact of flexible walls would be even lower. Another aspect that could reduce the environmental impact of flexible walls is changing the energy source used in steel production. Some speculate that in coming years hydrogen will play a more important role as an energy source than will fossil fuels.

The comparison of three wall systems with regards to their TC and their environmental impact indicates that transformable systems are not only favourable for flexibility in use, but can increase efficiency of our built environment, and accordingly its sustainability (Diagram 6.4).

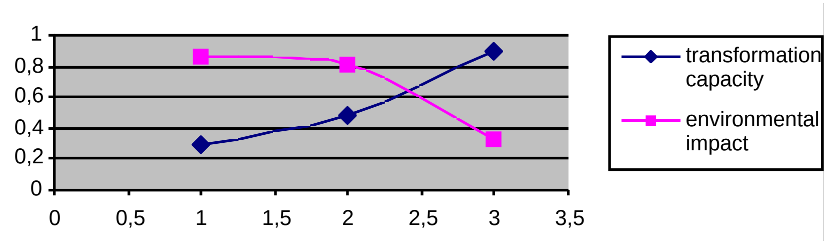


Diagram 6.4: The relation between levels of flexibility and environmental impact shows that high transformation capacity results in low environmental impact.

Taking into account the relation between TC and environmental efficiency established through comparison of three inner wall systems, one can argue that the transformable building with associated disassembly can be seen as a way to bridge the gap between people's prosperity and the efficiency of natural systems, by designing buildings that can be transformed on all scales from building to the material. In such a way buildings will have a greater ability to be adapted to changing human needs and at the same time can support cyclical material flows.

In the future development of the TC model it would be useful to relate TC calculations with environmental indexes. For example EcoQuantum and GreenCalc are software that assess environmental impact of building materials, which have an index that indicates environmental quality of the building. For example, according to the GreenCalc calculation XX building has environmental index 168. Such result indicates that the environmental impact of the building has improvement with factor of 1,6 compared to the building made in the year 1990. This model combines quantitative and qualitative aspects, such as emissions of materials and health aspects. When aspects of reuse potential are integrated, it is possible to make a relation between the environmental index and TC calculation. The framework developed in this research to assess the environmental impact of transformable structures could be implemented with additional optimisation into software such as EcoQuantum and GreenCalc.

Limitations of the model are subject to further optimisation.

The model works well for the case studies discussed in this chapter. These cases calculate TC with respect to reconfiguration of part of the building and to the total disassembly of the building. However, calculation of TC with respect to reconfiguration of all systems within a building and thus total building would be a complex time consuming procedure without prior formalisation of the assessment procedure.

- Recycling technologies

Furthermore, this model is primarily focused on separation of parts on site or in manufacturing facilities. This means that only general recycling technologies are integrated into the model such as the aspect of separation of materials that is not in favour of the use of composite materials. However, some composites can be treated in down cycling processes and some not. This difference has not been integrated into the model since down cycling in general is defined as at least beneficial.

- New deconstruction dechniques

The difference between different deconstruction techniques such as cutting a panel with a saw or lesser is not accentuated since these technologies primarily address aspects of faster deconstruction of the panel and not the reconfiguration of panel and recovering of its materials. However, there are some indications showing that development of deconstruction techniques with the use of robots can move towards more effective disassembly processes. In this case it can be considered for integration and application of deconstruction technology into the model, as well as one more in favour of transformation, until the material level using disassembly techniques can be obtained from the other.

- Economic factor

In order to relate TC calculations with economic factors in the future it would be necessary to attach the economic value of each component to the reuse potential, adding the savings in landfill costs as well.

Chapter 7
Design for high Transformation Capacity of structures

Transformable structures are essential for the global sustainability concept

INTRODUCTION

Conventional design is concentrated on the classic building properties that optimise function, construction, and costs, in relation to short-term performance.

Sustainable Development raises the need for integrated life cycle design, where all solutions are optimised and specified for the entire design service life of the building and its components. (ILCD2000)

The objective of this research is to introduce the concept of Transformation Capacity (TC), which is based on high disassembly potential of structures, as an integral part of the building/systems design. To achieve this it is argued that a better understanding of design process is required, since design for high TC can only be seen as a part of an integrated life cycle design. This is regarded as a process of synchronisation of design for disassembly (DfD) aspects, through a number of decision-making loops. As these aspects cover the range from functionality of an assembly to physical connections, they are embodied in almost all life cycle phases of a building. By their complex nature they have impact not only on the TC system but also as discussed in prvious chapters on social, economic, and environmental systems as well.

In the past, design was simpler, since it dealt with a smaller nummber of aspects, materials, and building techniques. Over time, new design aspects have emerged that must be addressed, such as shifts in world economies and markets, increasing competitive pressure on quality, time, and costs, ever-changing user requirements, energy efficiency, reuse, recycling, reduction in use of raw materials, sick building syndrome, etc.
Considering this, design decisions have an impact not only on the designed artefact, but also on a broader context, which extends far beyond the framework of a building construction phase.

Design decisions involving the typology of building configurations (that determines TC) have a major impact on building performance during operation, maintenance, transformation and the end-of-life phase of the building. More over, these decisions are directly related to the life cycle costs of a building, its environmental efficiency, and flexibility in use.

For that reason, design for high TC, based on a high disassembly potential, can be seen as a key integrating factor for sustainable design. In order to decouple continuous upgrading and transformation of the built environment from environmental harm, exponential increase in costs, and negative impact on social system, design for disassembly needs to be integrated into design at an early development stage.

7.1 DESIGN FOR HIGH TRANSFORMATION CAPACITY THROUGHT INTEGRATED DESIGN APPROACH

Architecture is no longer independent, but relieys on many different building specialists and partners during design and building processes. It has to be practical in relation to other disciplines, since architects deal with:
· changes that have taken place in the nature of the materials,
· increased speed of the construction caused by industrialisation of architecture,
· climate changes,
· life-style changes,
· technological changes,
· environmental issues

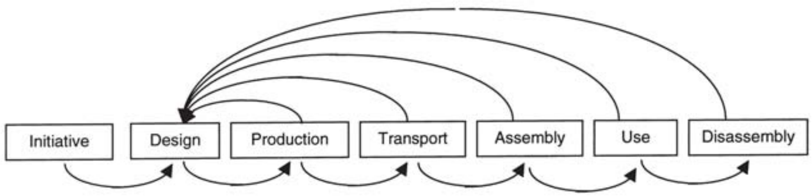


Figure 7.01: Integrated Life cycle design

These new conditions raise the need for integrated life cycle design, where functional, economic, environmental, operation, manufacturing, and construction/ deconstruction solutions are optimised for the entire service life of a building and its components.
During the design phase (one of the earliest phases) the greatest potential exists to influence the building properties for all subsequent life cycle phases. (Figure 7.01) A conventional design approach is regarded as hierarchical (Figure 7.02 left), in which elements of a hierarchical list of aspects are each studied separately. Due to such linearity and the hierarchical dependency in decision-making, a conventional design approach has limited capability in dealing with increasing complexity in building design. That is why a systems thinking approach - that relays on theory of levels (see Chapter 3) has been introduced into building design. Its strength lies in its focus on how the studied aspects interact with other constituents of the system, and the kind of effects these interactions cause. This

means that instead of isolating smaller and smaller parts of the building, systems thinking works by expanding its view to take into account larger and larger groups of interacting elements. Such a concept provides a framework for multidisciplinary teamwork that can influence the building design of cost-effective and high performance buildings.

When looking at transformation within such an interactive framework, one concludes that transformation (based on high DfD potential) is an essential element of a global sustainability system, since the TC has impact not only on the environmental system but on economic and social systems as well. Closing the loop of global sustainability system by means of high TC of structures can be described as follows:

TC has influence on social system in terms of providing users and stakeholders with the freedom to shape and reshape their requirements without affecting others. As a result, we have witnessed a movement in industry towards greater customisation of products. In order to cut costs, industry is looking into possibilities for reusing parts of building systems, recycling of materials, and design systems that are easy to replace, repair, maintain and whose parts are reusable and reconfigurable. Besides economic impacts, such an approach has a direct impact on environmental outcomes. Thus, design for high TC compresses issues of functionality, choosing of materials and their integration in a way that serves the goals of users as well as provides an easy transition of building products and materials form one function-material relationship to another.

For that reason the scheme representing design process for high TC is one that illustrates integration of teamwork from a beginning of a design process. This can be called ‘Architectural Engineering’. The team works on optimisation of a number of parameters in an interactive manner, rather than in a hierarchical order. The goal of such compressed design engineering is not just a building design but also production of two manuals that illustrate the building and material potential for long-term use (Figure 7.02 right). Manual 1 is the use and maintenance manual for the building and contains a number of scenarios for the building’s use. Manual 2 is the post-use manual that contains scenarios for treatment of components and materials after their use in one function-material relationship.

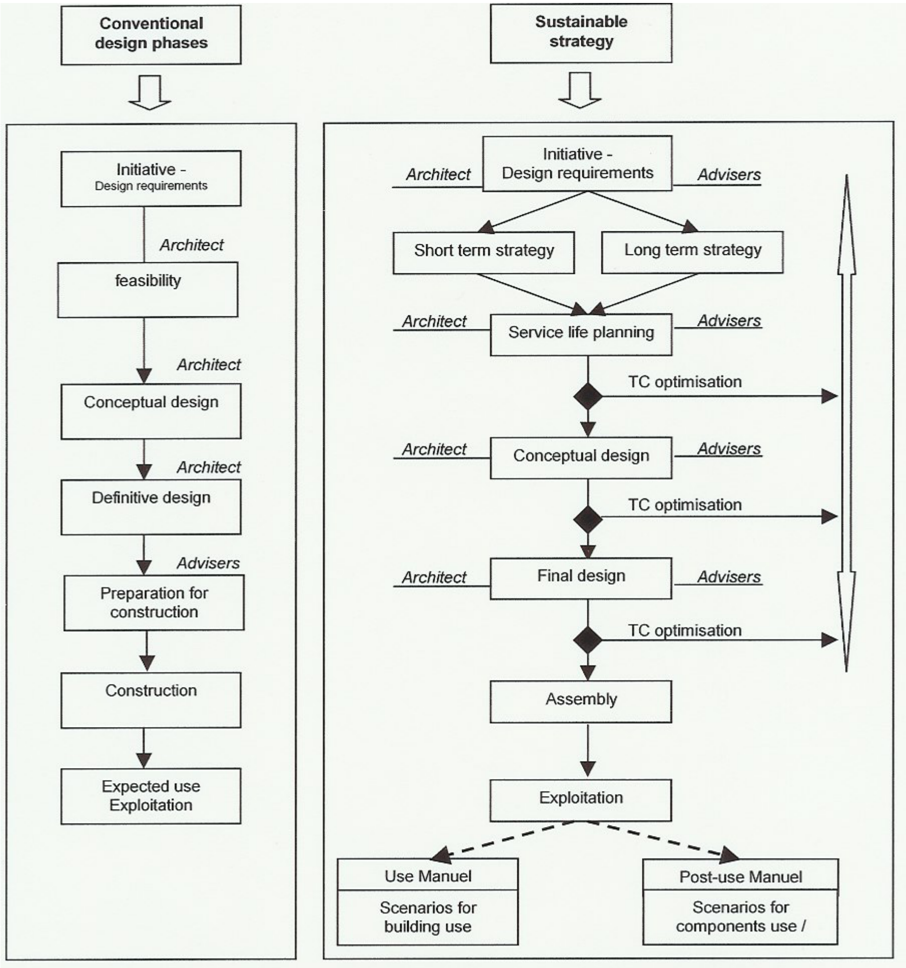


Figure 7.02: left conventional design phases, right sustainable design phases

The introduction of an integrated systems design aproach into building design means that the static hierarchy of decision-making, where each phase has to deliver specifics, is transformed into a dynamic decision-making process.
This results in step-by-step optimisations and, accordingly, into greater interaction between disciplines from the beginning of a design process.

7.1.1 Pioneers of systems design / integrated design approach

Studies related to product engineering that consider costs associated with a product during its entire life cycle, have demonstrated that between 60-90% of these costs are determined during the design phase. (C. S. Syan 1994) The earlier improvements are made, the greater is the cost reduction. (Diagram 7.1)

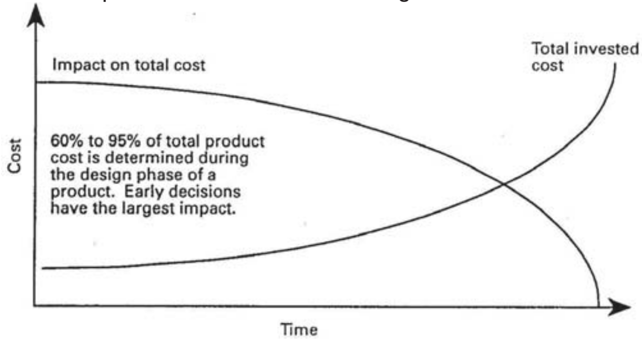


Diagram 7.1 :Relation between the moment of decision making and investment costs (C.S.Syan 1994)

The same study sums up another group of questions related to the increase of global competition and those that cannot be addressed by traditional design methods. Key trends that have influenced the competitiveness in product industries, but which could be recognised in building industry as well, are defined by Goldher as: the use life cycle of products is shortening, the diversity, variety, and complexity of products is increasing, and customers are becoming quite sophisticated and now demand customised products more closely targeted to their needs. This has led to pressures for continuous product improvements, leading to ever-increasing functionalities and typologies. As a consequence, product development time increases considerably. This is due primarily to the increasing complexity of products, while the product functional lifetimes have decreased.

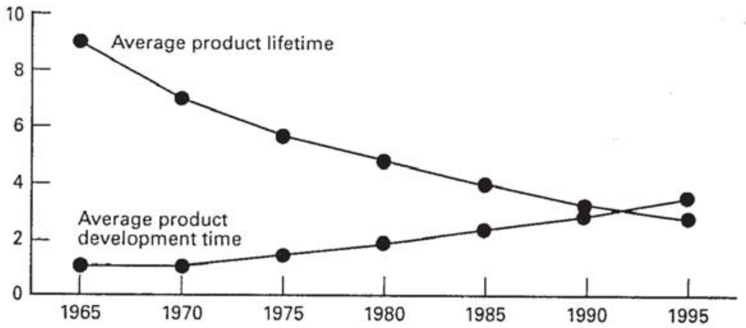


Diagram 7.2:Product development time versus the product's life time (C.S.Syan 1994)

Diagram 7.2 illustrates the trend of decreasing product life times and increasing development times. If development times are not reduced significantly while maintaining quality and keeping the costs down, the consequences for companies can be disastrous. They can be faced with enormous development costs as well as heavy price competition.

The Japanese car industry was the first to address this problem. The term 'concurrent engineering' emerged in the Japanese automotive industry in order to address problems of time, at the time when that industry began to dominate automotive markets worldwide. Two diagrams below illustrate the time-to-market of Japanese and European manufacturers. After adopting an integrated design approach, the Japanese industry was able to develop and market cars in half the time required by the European. (Diagram 7.3)

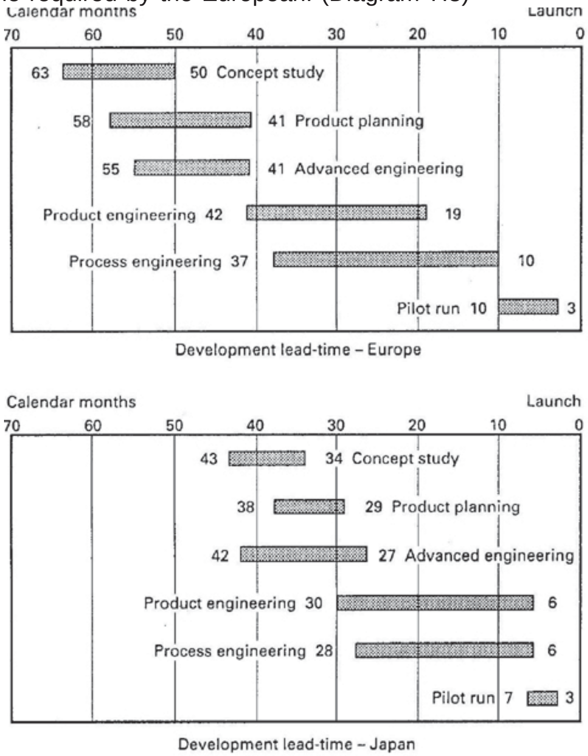


Diagram 7.3: diferance betwee concurrent engineering and conventional engineering approach (C.S.Syan 1994)

Western countries were slow to recognise the basis for this Japanese success. However, in 1986 the American Defence Advanced Research Project Agency began

a study into improving concurrency in the design process. In its report R-338, the Institute for Defence Analyses used the term ‘concurrent engineering’ to define a systematic method for product and process design. It also gave a definition of concurrent engineering, which is now widely accepted:
“Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related process, including manufacture and support. This approach is intended to cause the developers from the outset to consider all elements of the product life cycle, from concept through disposal, including quality, cost, schedule, and user requirements.” Concurrent engineering is often mentioned in the literature as ‘systems design’ or the ‘integrated design approach.’

A number of studies have indicated that systems design / concurrent engineering is the only way to deal with the increasing number of issues related to building design.(Quanjel 2003) Consideration of time aspects of design through all life cycle phases of building in the early design phase would increase considerably building sustainability.

7.2 DESIGN FOR DISASSEMBLY AS SYSTEMS DESIGN

Systems design (or integrated design) consists of an orderly protocol that leads to the best decision for a given set of conditions. Due to its generic approach, it is applicable to all types and levels of buildings. When properly executed, systems design enables designers to obtain a clear understanding of the requirements for a proposed building/system and can help owners and designers to evaluate proposed designs and select the best or optimum design.

Systems design procedures have three essential aspects for each decision-making step:
· Analysis (to indicate what the system is to accomplish)
Analysis includes identification of objectives and establishment of performance criteria for the product.
In other words, the analysis phase deals with requirements specification.
Requirements define a design problem and capture the key information needed to describe design decisions. The questions that must be answered during this phase with respect to transformation are when and wher edisassembly takes place.

These deal with specification of the service life planning of a building, which indicates criteria that the design should accomplish.

· Synthesis (formulation of a system that meets objectives and constraints).
Synthesis is the process of selecting components to form a system that meet design objectives.
In the context of design for high TC, the Synthesis phase considers eight additional aspect designs for disassembly aspects during selection of the objectives, building/system development, building/system analysis and selection of the best solution.

· Appraisal (evaluation of systems performance and costs).
Appraisal indicates the environmental and performance effectiveness of a design solution. Data obtained during an appraisal are used to effect improvements in the system through feedback of information to analysis and synthesis. Use of assessment models or development of prototypes of a system or part of the system can evaluate a system's performance. A model can also be a set of mathematical numbers, graphs, tables, or words.

Regarding the design for high TC, this phase deals with evaluation of a structure's TC according to the criteria of service life planning and communication of the results to the next design cycle.
These three steps (analysis, synthesis and appraisal) can be seen as elementary activities of a basic decision-making cycle.

The task of the DfD process is to give a form to a transformable building configuration defined by the functional, technical, and physical aspects of composition and decomposition. A DfD approach implies modelling of these aspects in an interactive manner. If we go back to the basic design cycle, we can define functional, technical, and physical domains of configuration as three design problems. *Analysis, Synthesis and Evaluation* of these three domains of configuration design form the basic design cycle in the DfD approach. (Figure 7.03)
Thus, each design cycle deals with three domains of configuration, from provisional to detailed decision making cycles. This process can be pictured as a number of

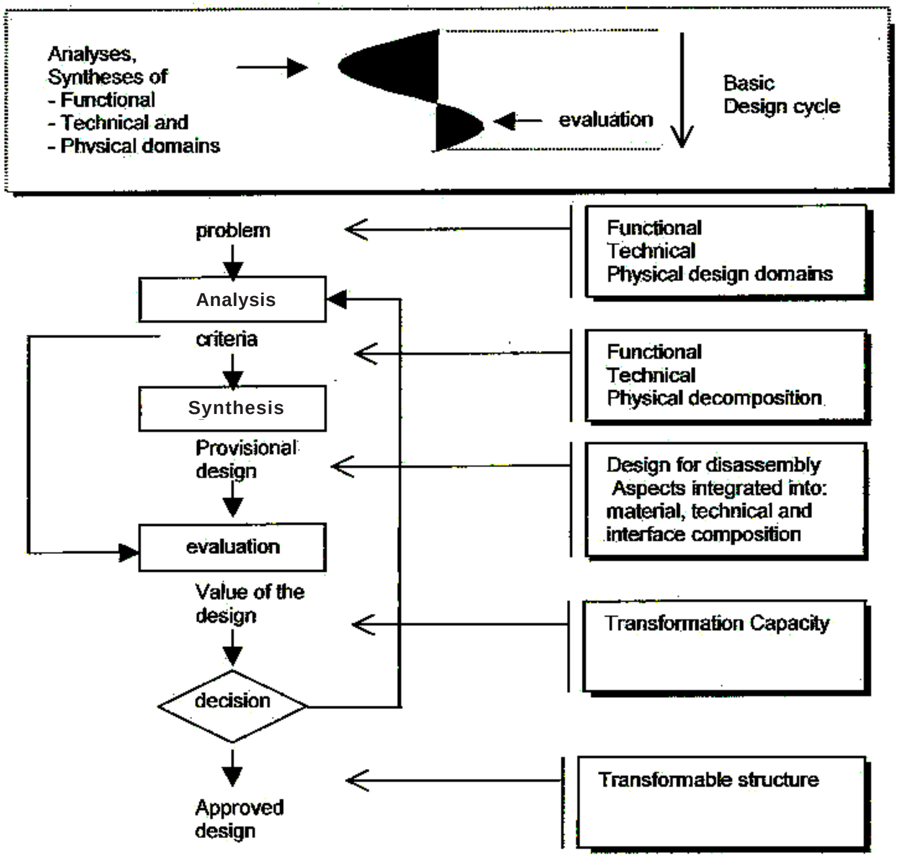


Figure 7.03: basic design cycle for design of transformable building

design loops as shown in the Figure 7.04. These loops correspond to the decision-making cycles regarding the functional, technical, and physical composition on different levels of abstraction. In the beginning of a design process, basic loops are the largest, since requirements are still not clearly defined and many aspects need to be researched. If information about some aspects is lacking, the designer may proceed assuming a default value for the information. Houwever, this decision is then regarded as tentative (Tichem 1997). After the missing information is generated, a tentative decision becomes a definitive decision. Within each new cycle, the process becomes more focused and project requirements more detailed, up to the point where the last unknown elements are defined. The cycle with sub-cycles can be repeated any number of times during the design process, while

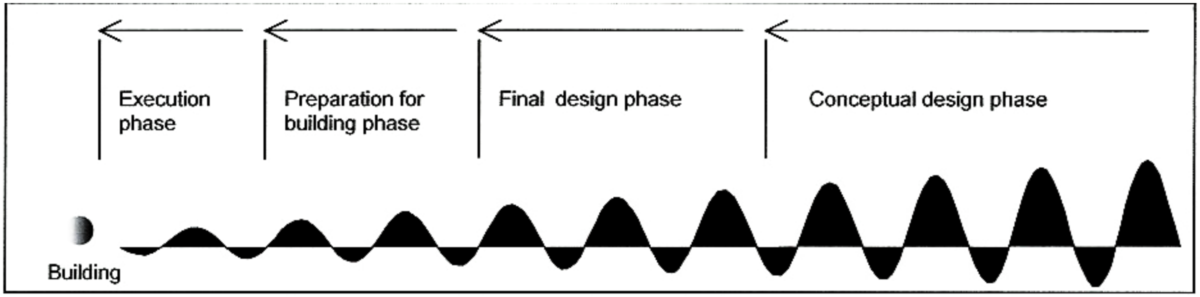


Figure 7.04: transformation of design cycles as design progresses from abstract to the end design solutions

moving the design from an abstract to an alternative and finally to a specific end solution.

Considering this, the DfD sub-cycle can be defined as:

1. Analysis of evaluation results and definition of requirements for the new design cycle.
2. Syntheses: improvement of the DfD aspects in order to increase disassembly potential and, accordingly, TC of the structure.
3. Evaluation of the improved solutions for the DfD and assessment of the TC of the structure.

7.3 DESIGN FOR DISASSEMBLY CONSIDERATIONS IN THE BASIC DESIGN CYCLE

The design process defines what a configuration can do. However, the analysis stages define how well a configuration must perform (that is, to a desired TC) and how a configuration can be tested to verify and validate its performance. To do this effectively, designers have to maintain a clear focus on the objectives that users and owners have defined for the building or system.
Focus on objectives is maintained by evaluation of design decisions made during the provisional design phase/ synthesis.

In later text, the three main considerations for DfD for each stage within basic design cycle are discussed.

7.3.1 Analyses – service life planning

The main task during analysis phase is to set the boundary conditions for DfD. The two questions that need to be answered prior to the start of DfD are when and where disassembly takes place.

The 'when' question is specified by defining the long term scenarios with respect to a building and its materials (see Table 7.1).

The 'what' question is specified by defining short term scenarios conserning the building and its materials (see table 7.2).

The method used to analyse these requirements can be called Service Life Planning which seeks to ensure, as far as possible, that the service life of a building equals or exceeds its design life.

Thus, during Service Life Planning, long-term and short-term requirements for a building need to be identified so that structures can be better designed to meet client needs, that resources are more efficiently used, and environmental impacts controlled.

As the length of service life cannot be known precisely in advance, the objective becomes to make an appropriately reliable forecast of the service life using available data.

The two main requirements of this DfD stage are definition of short-term and long -term scenarios for the building, which results in the design of short-term and long-term transformation strategies (Table 7.3). Short-term transformations focus on preservation of most of the material in its original state as long as possible, or by replacing them from place to place and using them for other purposes.

This is seen in a form of reuse of existing buildings, existing systems, or materials.

However, the technology, functionality, and aesthetics captured in one system or product are time dependent. This aspect makes them unsuitable for the long term. That is why development of scenarios for long-term transformation should also take place at the beginning of design processes

.

Long-term transformations focus on the transformation of systems and materials through processes such as reconfiguration and recycling that provides re-materialisation of used buildings and their materials. If design provides only short-term transformation without taking into account aspects of the re-materialisation, then the process of environmental degradation will slows down but does not stop.

	Long term strategy	**Definition**	**Destination of the building**
1	Time independent buildings	buildings that are frequently subject to transformations due to the market changes, social economic or whether changes	housing retail office schools floating houses
2	Specific buildings	buildings that are of the long term strategic interest, and therefore are less sensitive to market, economic and social changes	Hospitals Governmental buildings Sport facilities Banks Manufacturing facilities
3	Temporally buildings	buildings that have dynamic interactions with society and the climate these buildings can answer immediate needs of the society	Pavilions Expositions Information centres Kiosks Summer restaurants/cafés
4	Mobile buildings	buildings that are mobile because of climate conditions or life/work stile Mobile buildings could have all perviously mentioned strategies	floating house movable school floating pavilion

Table 7.1: Four long term strategies for the building

Thus:
DfD = Long Term strategy (table 7.1) = short term Transformation scenario (table 7.2) + long term Transformation scenario (table 7.3)

Short-term scenarios define the use scenarios of a building and its materials (Table 7.2).
They represent use scenarios regarding the spatial use, but also use scenarios for the system and its components.

Four general use scenarios are:
1 free repositioning of functional zones,
2 reconfiguration of functional zones,
3 internal rearrangement within a functional zone, free partitioning within one functional zone, and
4 extendibility of a functional zone (Table 7.2)

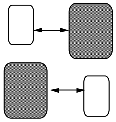
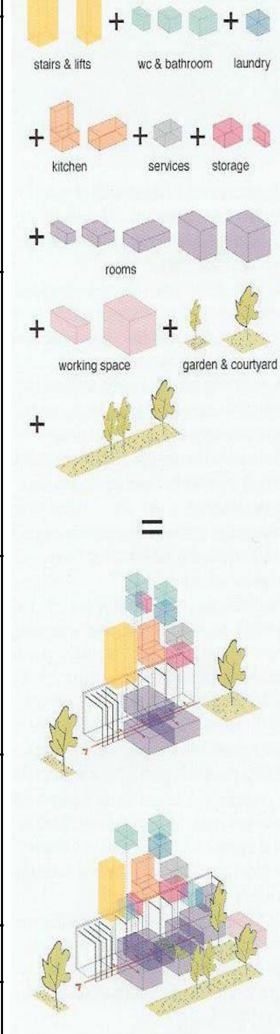
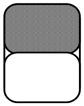
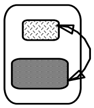
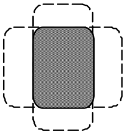
	Short term scenarios f for the use of configurations	Building strategies	graphical representation of the scenarios	Systems / Components Strategies
1	Free repositioning of the functional zones 	The ability to reposition different functional units within one building structure. This means that building function remains the same but its sub-functions can be moved from one location to another. bathroom units moved from one location to another		The ability to reposition different components within one system structure. This means that systems function remains the same but its components can be moved from one location to another. electric components within the wall
2	Reconfiguration of one functional zone (partitioning into another within the same structural constrains 	The ability to reconfigure one space from one function to another. That means that the space changes the function within the same structural constrains. multyfunctionality		The ability to reconfigure one function of the system into a new function. This means that the systems function is partly changed by insertion of some new components Facade system that in place of closed section introduces and open section Partitioning wall that in place of finishing panel introduces TV screen
3	Internal rearangment 	Free internal partitioning of one functional zone into sub-zones. For example, partitioning of office spaces. The main function is not changed, only the size of sub-zones		Free Internal partitioning of system into subsystems and components. For r example facade system whose components can be replaced from one location to another as shown on the example of Next 21facade system (chapter 3)
4	extendibility 	The ability to extend the building horizontally or vertically		The ability to extend the system by adding subsystems or components to it horizontally or vertically
5	combination of two strateg	free repositioning and partitioning		
6	combination of more that tv scenarios	free repositioning, partitioning and extendibility		

Table7.2: Table presents short use scenarios and corresponding strategies for design of buildings and systems or components

Short-term scenarios at the building level define the performance requirements for development of systems that are a part of a particular building. In other words, that form a building's configuration. These are at the same time short-term requirements for the system development (table 7.3).

However system development considers the long-term scenarios for system

components as well. The long and short-term scenarios at the building level define the use life cycle of the system and its components.
However the technical life of the system components determine the long-term requirements for the system's components.
Accordingly all configurations can be grouped into three groups, which are based on three lifecycle coordination scenarios:

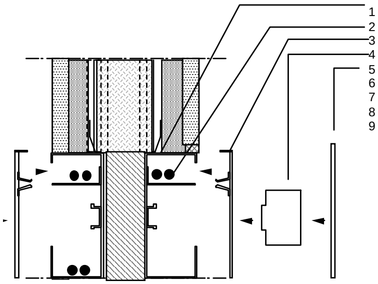
(i) Use life cycle of the component < the technical life cycle of the component. Here, design for reconfiguration, reuse, and recycling are crucial. Such components should be reusable or recyclable.
(ii) Use life cycle > technical life cycle of the components. In this scenario design for maintenance has a key role. Components should be replaceable and recyclable.
(iii) Use life cycle = technical durability (service life). Here, design for recycling is a dominant design requirement. Thus, all components should be recyclable.

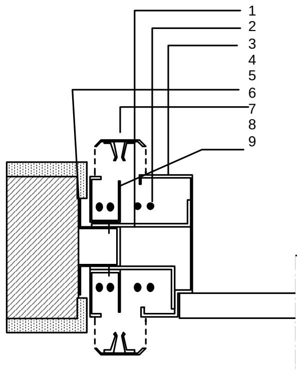
The matrix below shows the long-term scenarios with corresponding short-term scenarios and strategies, for the use of a building and its materials.

Table 7.3: Long term/short term scenarios and corresponding strategies

	Long term scenarios for use of configurations	**Short term scenarios for Use of configurations**	**Long term strategy For materials**	**Short term strategy For materials**
1	time independent building	Free partitioning	Disassembly on material level	Disassembly on building and system level:
		Reconfiguration	recycling	
	U.L.C < T.L.C	Internal rearrangement Extendibility		-reuse of variable components -reconfiguration
2	specific building	Internal rearrangement	disassembly on material level	Disassembly on component level:
	U.L.C > T.L.C		recycling	-replace for maintenance -reuse, recycling
3	temporally buildings	Internal rearrangement	disassembly on material level	Disassembly on material level:
	U.L.C = T.L.C		recycling	-recycling

Figure 7.05: disassembly of elements that have diferent functionality and technical durability





Thus, durability of technical systems can be shorter, equal, or longer than their use durability.

The question as 'where' does disassembly takes place can be answered through analysis of the life cycle coordination matrix. The life cycle coordination matrix accentuates the life cycle differences between materials and their functions. The matrix makes the designer alert when making decisions regarding the hierarchical composition of building systems and their components.

Life cycle co-ordination matrix evaluates life cycle co-ordination between systems functions and corresponding materials. It gives an opportunity to adjust the material choice or to integrate information from the matrix as input for the technical composition of a system.

If the matrix indicates that there is a great disproportion between the use and technical life cycle of components and materials then the configuration has to be designed for reuse, reconfiguration, or recycling. The design strategy depends on long and short term scenarios for the configuration.

The matrix shown in the Table 4 indicates that the reuse potential of all components increases on average by seven times if the configuration is designed for disassembly and reuse. During development of this configuration, it has been decided that all interfaces between components that have longer technical life cycle than expected use durability should be designed as click connections. (figure 7.05)

el.goot elements/components

	use LC / service LC	el.goot	viland cables	WCD	WCD-cover	goot-cover
		70	30	30	25	70
functions						
supporting	10	x				
enclosing	2_5				x	x
distributing	2_5		x			
separating	10					
outlets	2_5			x		

This LCC matrix indicates that high TC can be achieved if all components have high disassembly potential (Figure 7.05).

Every long- term scenario can result in a number of different short-term scenario. In addition, every short-use scenario can require a number of different strategies each having different use characteristics according to which the technical composition is designed.

Based on the number of combinations of functional zones that play a role in defining use characteristics of configurations on building, system, component level, the basic calculations indicate that every use scenario can result in 45 types of configurations on the building level and in a total of 450000 type of configurations, taking into account all building levels of technical composition (see table 7.4).

Functional zones in building use are defined as:	main functional building systems	main functionas within systems and components	on all building levels (builidng, system, subsystem,component,sub-component)
fixed wet units; toilets	frame	bearing,	
movable wet units	floor	partitioning	
spaces for daily accommodation	roof	finishing	
spaces for night accommodation	fasade	servicing	
service spaces	partitioning walls	fixing	
public spaces	installation walls		
special use	el		
	ventil		
	plumbing		
	heating		
no.of configuration types	45	10	450000

Table 7.4: Number of configuration types as a result of number of functional zones on all levels of building technical composition

In order to provide the right match between transformation scenarios and the technical composition of configurations that result in a high TC, optimisation of DfD aspects during the synthesis will play a major role.

7.3.2 Syntheses

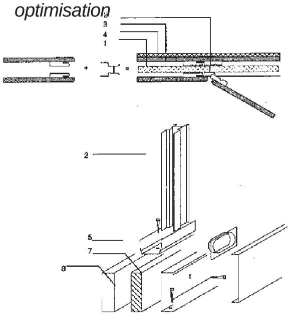
Syntheses (the development process) is seen as a decomposition process followed by re-composition (Forsberg and Mooz 1992). During the decomposition process, requirements are analysed and then partitioned into a set of specifications for systems, components, or elements. The key element in this phase is that this process be broad in perspective such that nothing is left out. This is achieved by repeating the design sub-cycles a number of times until the system's specifications are sufficiently detailed for individual configuration items to be built.

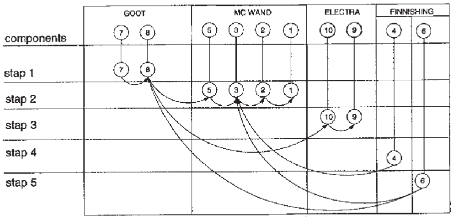
The ddesign phase focuses on problem definition, selecting objectives, systems synthesis, system analyses selecting the best system, and on communication of the results. These activities are repeated in a number of design cycles, on different levels of design abstraction.

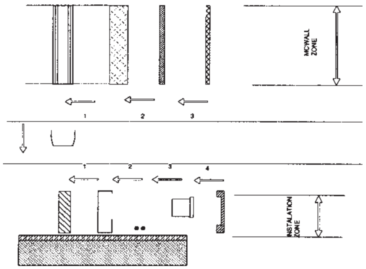
The DfD aspects that are of consideration during syntheses phase are:
· functional separation,
· systematisation of elements according to the functional groups,
· formation of a hierarchy of components that fits into a desired functional decomposition,
· specification of base elements that fit a desired hierarchy of elements and functional decomposition,
· definition of assembly sequences that support desired functional and technical decomposition,
· definition of types of connections that support assembly sequences and accordingly, desired functional, and technical decomposition,
· design of the geometry for connections that support the type of connection, assembly, and functional, and technical decomposition, and
· life cycle coordination that respects disassembly sequences, technical, and functional decomposition.

Practical application of these aspects during system development are shown in the case of the SMR development. (Figure 7.06)
The diagrams shown bellow represent design solutions regarding the SMR system and their optimisation, as a result of the consideration of above-mentioned DfD aspects. Figure 7.06 right shows a relational diagram, functional dependence, hierarchy of components, and corresponding assembly sequences
of the first proposal. While Figure 7.06 left illustrates characteristics of the configuration after optimisation.
The relational diagram of the first proposal represents one close and static configuration with large degree of functional dependence.
Opposite to this, the solution for the optimised design proposal is represented by a relational diagram that indicates an open structure, with clear separation of functions and base elements within each functional group.
During system development of the SMR, a number of design cycles and subcycles

Diagram below show
Second design cycle - Results of design optimisation







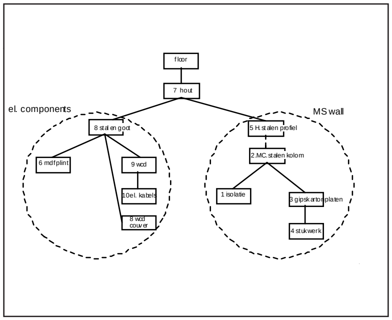


Diagram below show
First design cycle - First design proposal

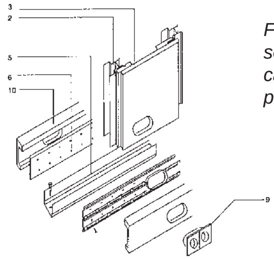
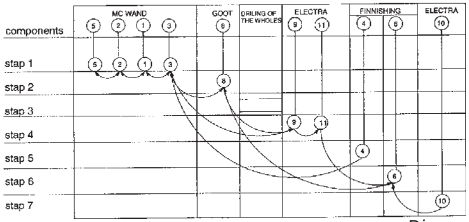
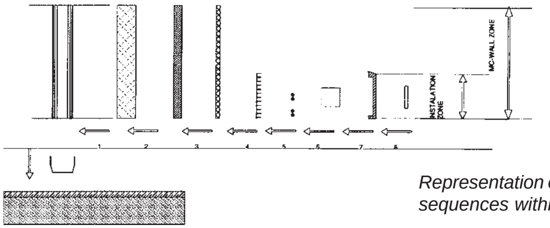


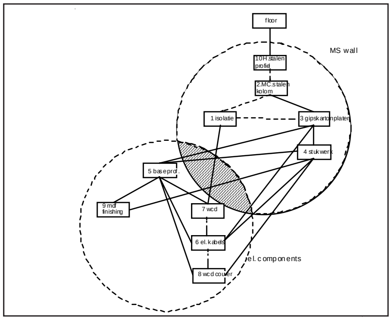
Figure 7.06: Evaluation of design solutions with respect to transformation capacity during system development phase



Diagrams represent dependencies in assembly



Representation of assembly/dependence sequences within designed concepts



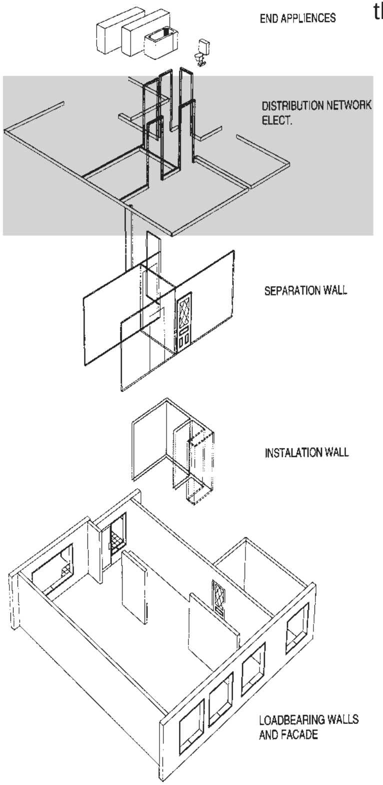
Relational diagrams illustrate dependencies between building components and their functions within designed concepts

deal with improvements of the system that have resulted in higher TC and environmental efficiency (this has been discussed in Chapter 6).
Table 7.5 indicates that improved DfD aspects after optimisation of proposed design solution. While the net graphs below illustrate improvements to the TC of the partitioning wall system per DfD aspect.

The net graph on the left represents the DfD aspects within a conventional partition wall. (Diagram 7.4) The graph in the middle illustrates the DfD aspect achieved by the proposed design, while the graph on the right illustrates the DfD aspect after the optimisation phase.

Table7.5 : Representation of the improved DFD aspects

Aspects	Sub aspects		during optimisation
FD	functional separation	fs	
	functional dependency	fdp	x
SYS	structure and material levels	st	
	clustering	c	x
BE	base element specification	b	x
LCC	use life cycle coordination	ulc	
	technical life cycle coordination	tlc	
	LCC in relation to the size	s	
RP	position of relations	r	x
A	assembly direction based on type of assembly	ad	x
	assembly sequences and material levels	as	
G	geometry of product edge	gp	x
	standardisation of product edge	spe	x
C	type of connection	tc	x
	accessibility to fixings and intermediary	af	x
	tolerance	t	
	morphology of joint	mc	



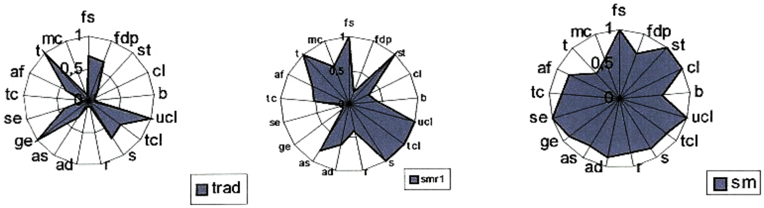


Diagram 7.4 : Net Graph representing design for disassembly aspects

7.3.3 Evaluation

In order to have an understanding of the impact that design decisions have on the disassembly potential of structures and accordingly on the environmental, social and economic systems, a knowledge model is proposed that assesses the TC of designed structure.
In such a way, design decisions can be evaluated regularly and accordingly optimised for the most sustainable performance of building and its materials in the future.
This assessment model gives an overview of the disassembly aspects of the design, which can be improved, in order to design transformable structures with a high disassembly potential for their parts.

If the transformation capacity is lower than 0,6 then optimisation of some design aspects in a new design cycle should be done in order to increase the disassembly potential of the configuration and reduce the negative environmental, economic, and social impacts that such structure can have in a long run.

This research focuses on the relation between TC and environmental efficiency. It has been concluded that the advantage of transformable systems, with respect to environmental pressure, grows with the increase of their changing sequences. The main advantage of transformable buildings and systems is in their reuse of parts, whose use life cycle is much shorter than their technical life cycle. With the example of two wall systems (flexible and block wall), it has been calculated that a transformable wall, which is made of demountable components and is replaced seven times (during its total life) saves 4776 tone/year of raw material, and provides reduction of waste of 5292 tonne/year. This results in the reduction of annual CO2 emissions to 18536 tonne /year (EET report 2004)

This research contributes to a better understanding of the impact that different types of building configurations have on the environment. It highlights aspects of building transformation, which have direct influence on the environmental efficiency of buildings and suggests a different approach to design, which can reduce the negative impact of buildings on the environment.
The information gained in this research is of significant importance to the life cycle assessment models as it provides a method to assess the environmental

efficiency of transformable structures and compares them with conventional structures.

7.4 DESIGN FOR DISASSEMBLY PROTOCOL

Considering all of the above, a design strategy for disassembly has been summarised in the figure 7.07.
The framework for DfD illustrated in figure 7.07 can be described as follow:

- In the initial phases of the building process, short and long-term strategies have to be determined. This results in the development of different scenarios for use of the structure. According to this, a hierarchy of technical systems is constructed.

· Definition of the performance indicators through specification of use scenarios on building and system level, which form the basis for design of a transformable building and system.

· As a part of the analysis phase, performance indicators help to provide short term and long term transformation scenarios according to which functional decomposition and material levels can be defined. Performance indicators guide the design during configuration design, which is seen as a type of synthesis.

· The life cycle coordination matrix indicates the disassembly-sensitive parts of the system. (At this point designer can optimise the matrix by reducing or extending the technical life cycle by choosing other materials, or by allocating other functions to the existing materials, which are accounted for the great life cycle disproportion. Such optimisation of the life cycle coordination matrix is directly related to the reconfiguration of the structure or functional decomposition).

· Based on the specification of use strategies, a design proposal for the configuration is made. This stage of decision-making recognises a number of optimisation steps which do not make it independent of other decision-making processes. If a structure is represented by a closed hierarchical relational diagram, then re-structuring should take place. This can result in the change of material levels, or change of functionality.

· The physical decomposition stage deals with the pure physical aspects of relations between two components. However, these design variables depend on a number of other design aspects as assembly sequences, number and hierarchy of relations, and therefore are directly related to previous design aspects namely hierarchical composition and definition of material levels.

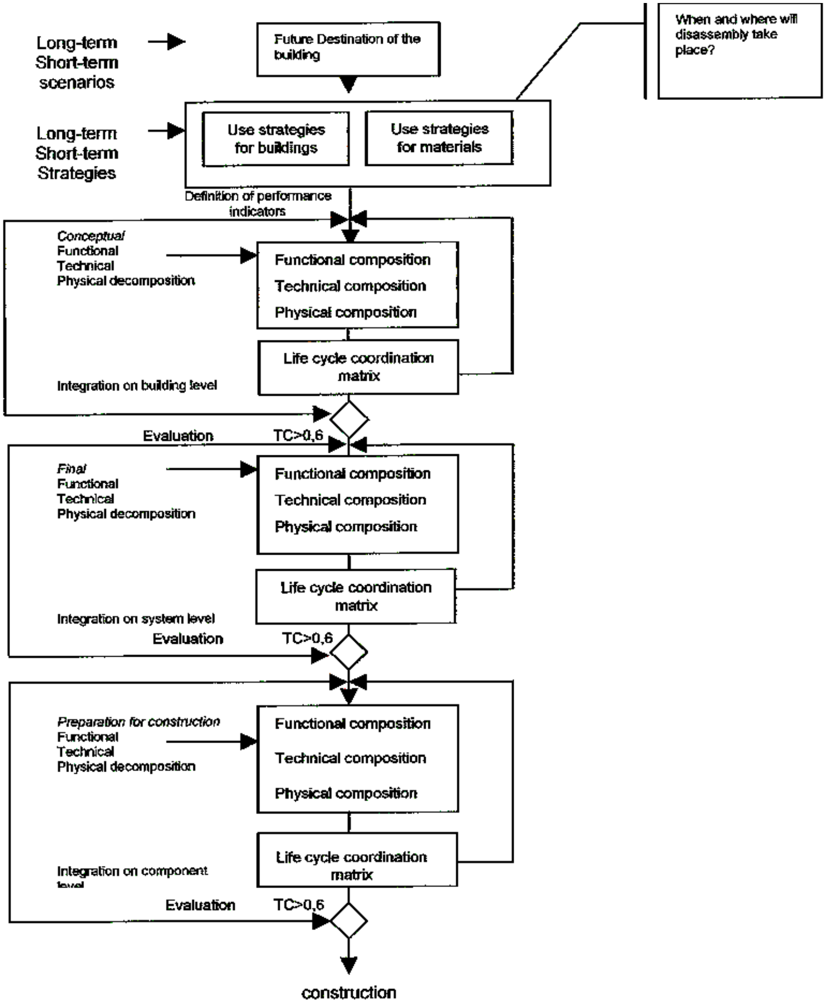


Figure 7.07 design scheme

Table 7.6: Design principles for deconstruction per design phase.

	design phases	design principles
1	feasibility phase	strategy planning outline scenario planning
2	conceptual design	scenario planning functional decomposition systematisation outline assembly disassembly planning design of open configuration (integration of the systems on the building level) initial evaluation of the Transformation capacity on the building level
3	definitive design	optimisation of the structure according to the evaluation results finalise short teem and long term scenarios for the building finalise configuration on the building level design of an open configuration (integration of the components on the system level) evaluation of the Transformation capacity on the system level
4	preparation for construction	optimisation of the structure according to the evaluation results design of open an configuration (integration of the elements on the component level) outline the manual for maintenance and handling of structures specification of reusable and recyclable elements
5	construction phase	outline of user manual for building systems and components
6	operations phase	use manual post use manual
7	transformation phase	assessment of suitability of the structure for a specific transformation scenario specification of reusable systems; development of operational building model user manual
8	dissasembly phase	development of an optional plan for reusable components

- Evaluation of TC

This protocol is applied a number of times during the final design phase on the system level and during preparation for building phase on the component level.

Considering all of the features of DfD defined above, the relation between design principles and design phases are shown in the Table 7.6.

An essential element of the whole concept is the provision of an open building configuration whose systematisation is based on principles of clear separation of materials and components with different functions, use life cycles, and technical life cycles.

In addition, when finalising DfD, aspects such as open hierarchical structure, specification of the base element on each building level, provision of assembly/ disassembly plan, and design of demountable connections ensures that the structure is 100% transformable.

The enactment of DfD shown in Table 6 is based on DfD guidelines, which are presented in the appendix 1. The guidelines are give for each building level of technical composition.

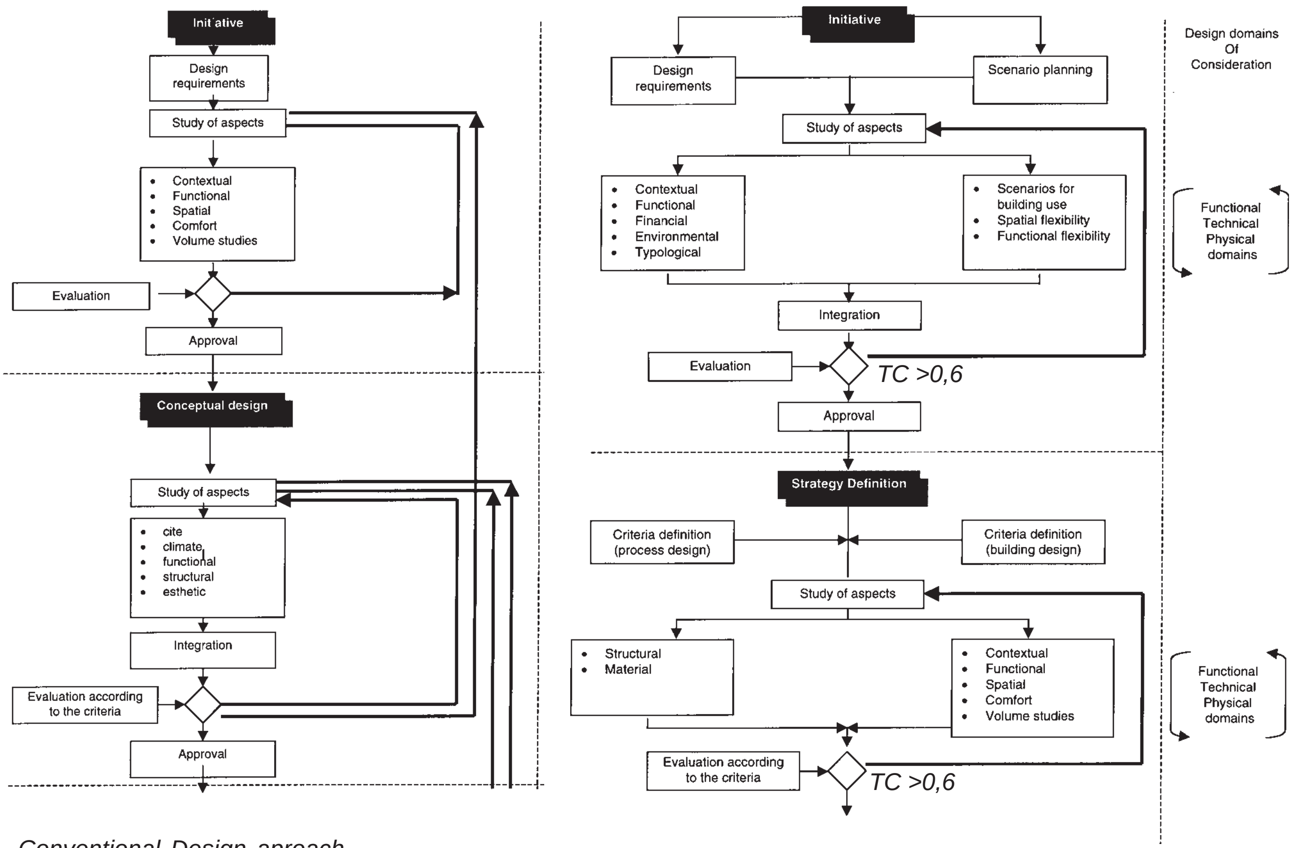
7.5 RISK ANALYSES OF THE TWO DESIGN METHODS

In order to maximise the performance of transformable structures, this research suggests an integral approach in the design of building/system configurations. It is argued that three components of configuration are interrelated and cannot be viewed separately during a design process.
Their specification within the design process determines the typology of configuration, with respect to its transformation, and end-of-life scenarios for building components and materials.

Diagram 7.5 left represents the hierarchy of the design phase model in a conventional step-by-step design process. The main characteristic of such a design model is that the design domains are separated through a hierarchical structure into distinct design phases. The first phase deals primarily with the functionality of the building structure. The second phase deals with technical composition, and the third phase with physical aspects of the structure. The phases are more or less defined before a subsequent phase begins. (Diagram 7.5 left) Such an approach has the potential risk of involving redesign of the early design phases at the and of a design process. This linear approach can be applied for very simple building configurations, which are defined on one building level and through one design cycle. However, sustainable structures are complex configurations because they have to be able to do more in order to survive over longer periods of time. Thus, sustainable structures are defined not by single levels but by the level of integration of systems , components, and elements on all levels of technical composition. Each of these levels deals with functional, technical, and physical design aspects, as a design process progresses from abstract and tentative solutions towards final ones.
If these aspects are analysed separately, then there is the risk that some design phases must be reconsidered at the and of a design process, or in a worst-case scenario, the design concept must be changed in a later phase because not all aspects have been well considered.

By applying an integrated systems design approach , design processes constantly improve a design with each decision-making cycle, through optimisation of disassembly aspects of each building's life cycle phases.(Diagram 7.5 right) The result of such design is an optimised structure, in which no improvisations are left for other life cycle phases of the building. This results in controlled material flows and low total life cycle costs.

Design Phases

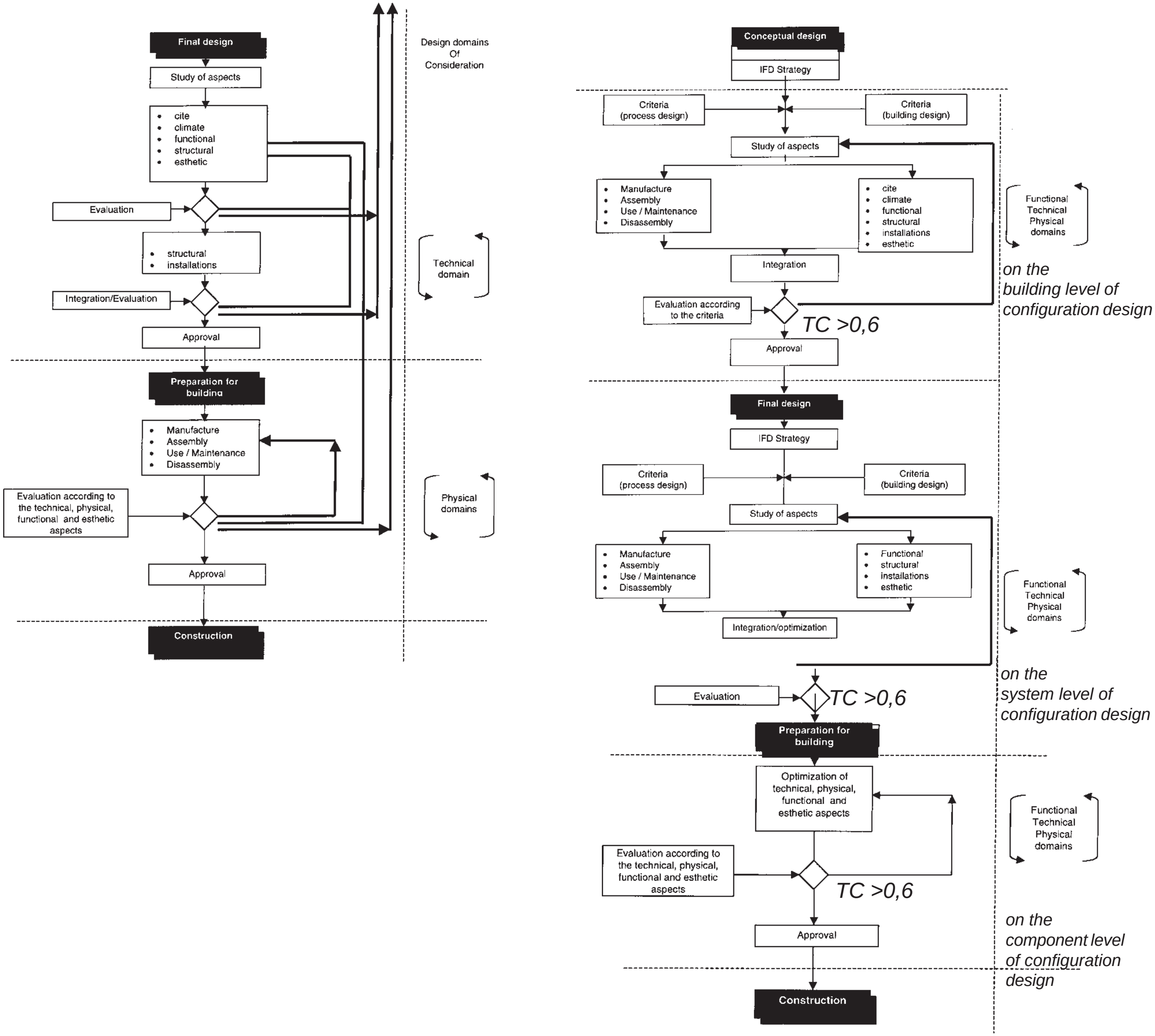


Conventional Design aproach

Integrated Design for Disassembly aproach

Diagram 7.5: Two design approaches

Diagram 7.5: Two design approaches



Integrated Design for Disassembly aproach *Conventional Design aproach*

Apendix 1

Design for Disassembly Guidelines

	scenario 1 ulc < tlc			*scenario 2* ulc > tlc			*scenario 3* ulc = tlc		
DESIGN GUIDELINES	**Building level**	**System level**	**Material level**	**Building level**	**System level**	**Material level**	**Building level**	**System level**	**Material level**
• Define use strategy for the building	●			●			●		
• Define functional decomposition of the building through the specification of fixed and changeable parts of the building,	●								
• Develop life cycle coordination matrix in order to define the point of disassembly	●	◆		●	◆				
• Design complex structures which can change functionality in the course of time	●	◆							
• Design base element as an intermedier between systems, components and elements	●	◆	►		◆	►			
• Design base element of each system and components	●	◆			◆				
• Optimize the structural grid to materials in order to make the most efficient use of material properties and therefore use less material (P.C)	●	◆		●	◆		●	◆	
• Provide a sufficient information about the building/ systems configurations their reconfiguration possibilities and their capacity for reconfiguration, reuse, recycling	●	◆	►	●	◆	►	●	◆	►
• Provide separation between major building functions such as load-bearing structure, facade, installations, partitioning elements end finishing	●			●					
• Define material levels following the functional decomposition		◆							
• Cluster materials into subassemblies according to their functionality, use life cycle, material, technical life cycle		◆							

DfD guidlines with respect to three life cycle coordination scenarios
scenario 1: use life cycle < technical life cycle
scenario 2: use life cycle > technical life cycle
scenario 3: use life cycle = technical life cycle

DfD guidlines with respect to three life cycle coordination scenarios
scenario 1: use life cycle < technical life cycle
scenario 2: use life cycle > technical life cycle
scenario 3: use life cycle = technical life cycle

	scenario 1	*scenario 2*	*scenario 3*
• Cluster materials into subassemblies according to material, technical life cycle		◈	◈
• create separation between the elements with different functional and life cycle expectances by using separate construction systems	◈	◈	
• Define an open hierarchical structure by avoiding functional and assembly relations between different functional groups	◈	◈	
• Design an open building system whose elements are independent and exchangeable	◈	◈	
• Use modular dimensional systems that are compatible with other systems	◈	◈	
• Base element/intermediary should be the most durable elements within the clusters	◈ ▶	◈ ▶	
• Use pre-assembled assemblies for the reason of faster and easier construction on the building site. In this way building, systems or components will be disassembled in two phases on the building site an in the workshop. This results into greater control of the material flow	◈	◈	◈
• Define the building through the building sections that could be independently produced and assembled	◈ ▶	◈ ▶	◈ ▶
• Define building systems suitable for repetitive manufacturing processes while retaining variation and irregularity	◈	◈	
• The connection between two independent clusters should be suitable for their easy decomposition and reuse,	◈ ▶	◈ ▶	
• Use light weight components which are easy to handle and transport	◈	◈	◈
• Use small size components which are part of larger assembly in order to increase the possibility for variations	◈		
• Design connections between changeable components to withstand multiple disassembly and reuse by use of well engineered base elements and intermediary between changeable components	◈ ▶		

	scenario 1	*scenario 2*	*scenario 3*
• Use minimum number of different types of fasteners and connection geometries	◈ ►	◈ ►	◈ ►
• Provide tolerances to allow disassembly of individual parts	◈ ►	◈ ►	◈ ►
• parallel assembly should replace sequential assembly in order to allow disassembly of single part without disruption to other parts, and for faster disassembly	►	►	►
• keep all components separated avoiding penetration into other component or system	►	►	
• provide accessibility to the components with shorter life cycle	►	►	
• mechanical connections should replace chemical connections	►	►	►
• Provide intermediary between base elements which belong to different clusters	►	►	►
• The clusters should be assembled in systematical order that is suitable for maintenance and replace ability,	►	►	
• assembly sequences should be designed with respect to type of material, its performance and life cycle;	►	►	
• The connections within the cluster should be suitable for recovery or recycling of single part.	►	►	►
• Provide material information	►	►	►
• assembly sequences should be designed with respect to type of material			►
• Avoid using composite materials unless they can be recycled without creating negative impact on the environment.	►	►	►

DfD guidlines with respect to three life cycle coordination scenarios
scenario 1: use life cycle < technical life cycle
scenario 2: use life cycle > technical life cycle
scenario 3: use life cycle = technical life cycle

Chapter 8
Conclusions and Recommendations

In the future, a quality of a building will be measured by its ability to transform on all levels of technical composition.

8.1 THE MAIN FINDINGS AND CONCLUSIONS

The main findings and conclusions of this thesis could be summarised into two groups:
1. Findings and conclusions regarding Design for Disassembly (DfD) as a tool to integrate green engineering in building design, and to increase the Transformation Capacity (TC) of structures.
2. Findings and conclusions regarding a knowledge model developed to evaluate the TC of structures, which is based on the disassembly potential at the end of use or technical life cycle of structures.

8.1.1.Conclusions regarding the Design for Disassembly framework

The moment when systems start to transform is the moment when structures can be reconfigured and reused, or simply demolished and sent to waste disposal sites. At that moment, the nature of the systems configuration is crucial for decision making. Ultimately, the configuration's typology defines a life cycle of buildings and their impact on the environment, the economic system, and the quality of life. Thus, it is not only a type of material(s) but also an arrangement of materials that determines the life cycle of buildings and their products.

Decision making dependency from the early design phase
This research points out that to understand and predict systems behaviour at the moment of transformation, it is important to recognise a life cycle duality is present in each building and system's structure. This duality has to do with the functionality of structures and their use life cycle on one hand, and type of materials and their technical life cycle on the other.
The 'function/material' relationship is treated as an ultimate unity during the design and construction process, which results in fixed relations between materials and their functions. If the functionality of an assembly changes, materials are disposed and new ones are used for the new function. Such a predefined end-of-life for each 'material function' relationship becomes a bottleneck for the transformation of assemblies based on disassembly. Instead of designing one 'function-material' relational set at the time, it becomes necessary to design a flexible framework that

allows reconfiguration of functions and materials without creating negative effects on the environment.

Therefore, Design for Transformation addresses the breaking point for functional or material use. It addresses issues related to functional flexibility as well as the flexibility of material levels and physical integration of these levels. Due to the interdependence between functional, technical, and physical aspect design of transformable structures, decisions regarding functionality influence a number of material levels and the type of their physical integration. At the same time, decisions regarding the hierarchy of materials and their physical integration have an influence on the independence of material levels and their functions. Thus, there is a constant interaction between the *'what'* and the *'how'* of design during a design of transformable buildings. If a design ignores this interdependence of decision-making, it may result in a closed configuration with fixed material-function relationships.

To illustrate this, two designs of wooden structures are shown in Figure 8.01.

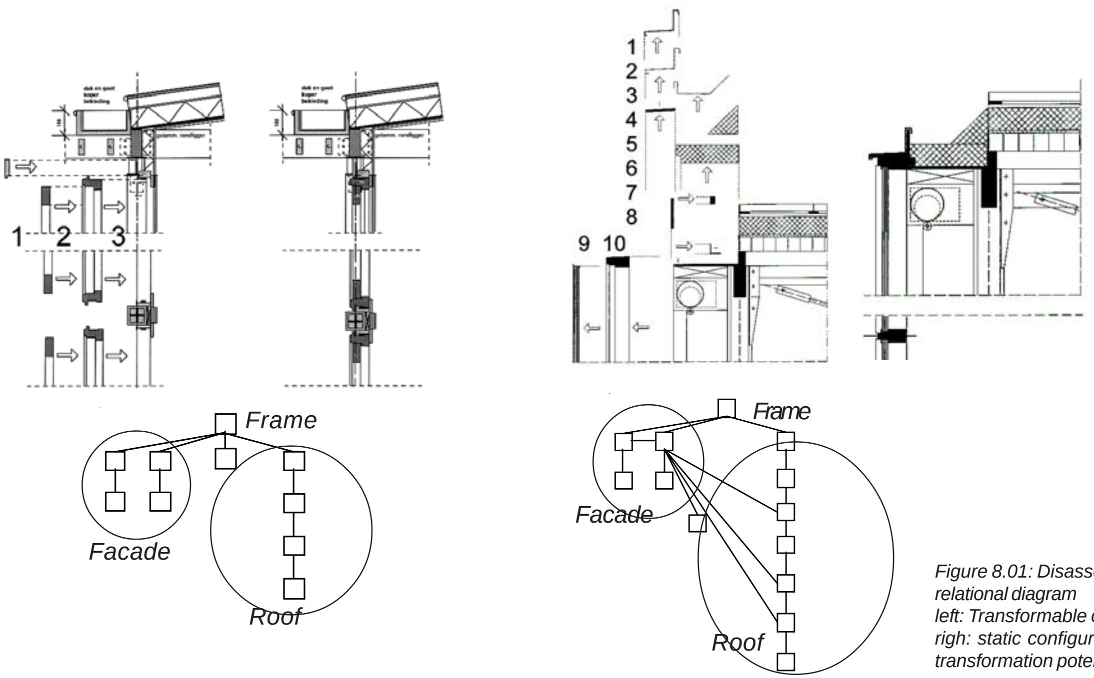


Figure 8.01: Disassembly hierarchy and relational diagram
left: Transformable configuration;
righ: static configuration - lack of transformation potential

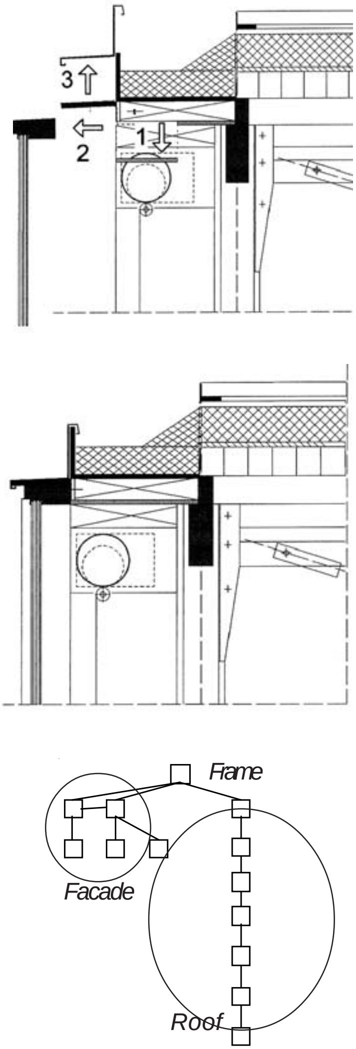


Figure 8.02: Optimised configuration for disassembly and reuse (increased Transformation Capacity)

One represents a transformable design approach (Figure 8.01 left) and the other a conventional design approach (Figure 8.01 right). In both these designs a starting point was the disassembly of their components. Although both designs are a result of a careful functional decomposition followed by an integration of the carefully designed independent subsystems, their configuration types are totally different. The relational pattern of the building assembly in Figure 8.01 (left) is open, indicating a transformable structure, while the relational pattern of the building assembly in Figure 8.01 (right) represented by a stack and a closed assembly type with a functional dependency. This indicates a structure that is difficult to transform. A major problem of the conventional design approach (Figure 8.01 right) is on its focus on functionality from the beginning of the design.

On one hand, such a design provides a clear functional decomposition according to the systems and components to be designed. On the other, when integrating carefully designed systems and components during a definitive design stage, configurations can become closed and may not be able to transform due to the lack of a strategic and integrated design approach in the early design phases.

To optimise the configuration shown in Figure 8.01 (right), to obtain a high TC, changes of some early design decisions should be made that involve a fundamental redesign of functional decomposition, a specification of the base element, and design of the component edge, etc. (Figure 8.02)

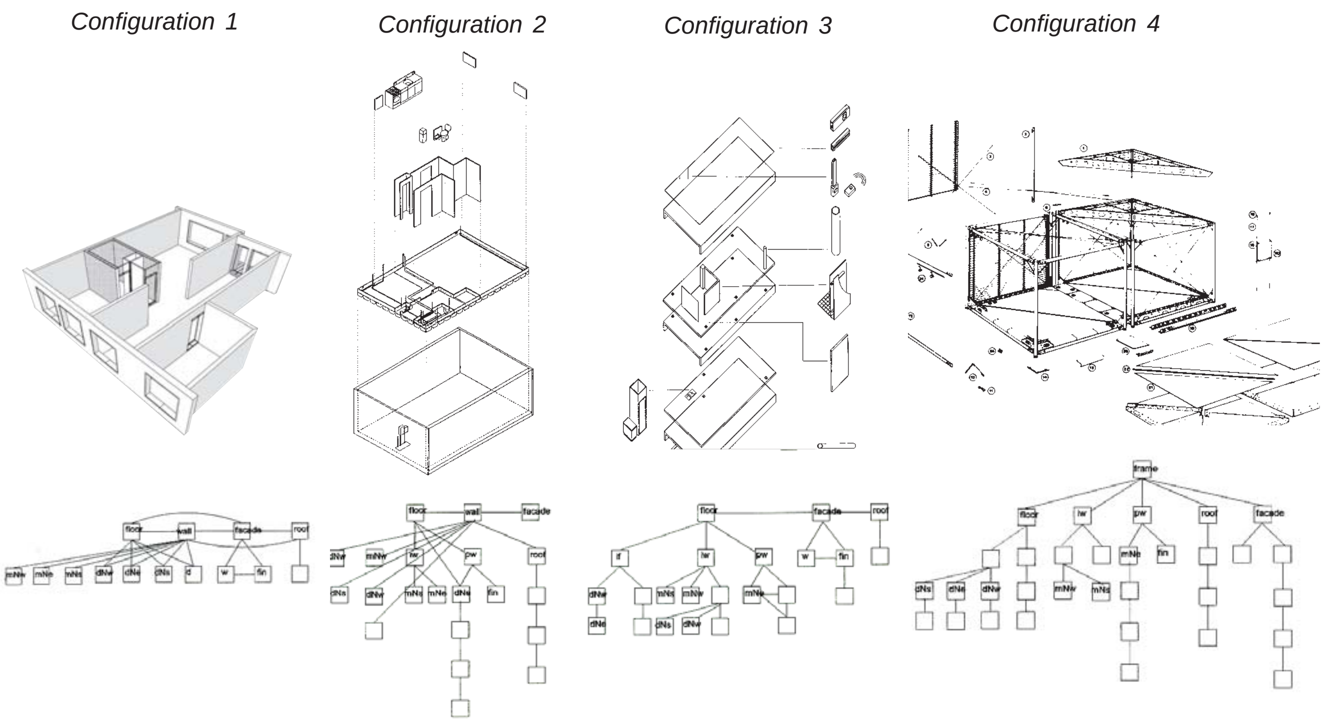
Redesigning in a later design phase is often costly and unfeasible, yet these decisions ultimately determine the impact of the structure on its environment and operational phase. In order to implement a conscious decision-making process that involves all life phases of a building, a systematic consideration of DfD aspects should be done from early design phases.

Design for Disassembly protocol

Design for transformation, based on the disassembly potential of materials, addresses a moment of change of the purpose of the assemblies. It addresses the moment when the rearrangement of materials takes place. A good understanding of the requirements that takes into account the long-term purpose of the artefact is crucial in the DfD approach. Scenarios for the use of building and building material in the future have to be defined at this early stage.

Every use scenario for a building or a system results in different technical compositions and different configuration types. Figure 8.03 illustrates four different configurations that match four different long-term use scenarios. Configuration 1 addresses a fixed use pattern for the whole design life of the building. Configuration 2 addresses flexibility that deals with the inner partitioning of a space, and introduces a floor and wall system that can be reconfigured and replaced. Configuration 3 addresses spatial flexibility that introduces a flexible concept for electrical installations imbedded in movable walls. Configuration 4 addresses a concept for the total flexibility, introducing systems that can be reconfigured and replaced. (Figure 8.03) Taking into account of the more than 450000 different configuration types (see Chapter 7) the key issue in the design of transformable structures is the definition of the right match between the long-term use strategies and the type of configuration. Taking into account the interdependency between the main factors that play a role in this process, this match can only be found through a systematic optimisation of functional, technical, and physical integration.

Figure 8.03 Hierarchy of the components representing four diferent configurations



Design for disassembly can be summarised into six essential steps:

• Definition of the use performance through specification of long and short-term scenarios;

• Functional decomposition followed by the initial specification of materials;

• Development of a life cycle coordination matrix for the proposed solution that indicates sensitive parts for disassembly;

• Definition of a hierarchy of material levels that corresponds to the frequency of change of building components for the purpose of maintenance and functional change;

• Outline of the physical integration between parts that have different functional and technical life cycle;

• Evaluation of a design solution by use of a knowledge model to match design solutions with desired performance indicators;

8.1.2. Findings and conclusions regarding the assessment of Transformation Capacity by use of a knowledge model

Systematic optimisation of design solutions is a main characteristic of a disassembly process that successfully implements a systems approach for DfD evaluation of design solutions. This research introduces an evaluation model that helps designers assess the disassembly potential of a building based on decisions that were made on different building levels, so that:

• Evaluation on the building level indicates functional, technical, and physical decomposition between the main systems based on defined use scenarios of building;

• Evaluation on the system level indicates functional, technical, and physical decomposition between the components of the system, based on defined use scenarios of systems;

• Evaluation on the system level that indicates the functional, technical, and physical decomposition between the elements and materials within components, based on defined use scenarios of components.

The knowledge model for assessment of TC proposed in this research is used to compare individual aspects of transformation. Assessment of aspects and their impact on the TC, which results in a final TC-index, are developed in such a way that evaluated configurations can be divided into the following three groups:

1. Configurations that have TC<0,3 are fixed – non-transformable configurations whose components are being sent to land fills or down-cycled after they have served their function.
2. Configurations that have 0,3 <TC<0,6 are partially transformable configurations. Around 50% of components are recovered for up-cycling and reuse after they have served their function.
3. Configurations that have 0,6 <TC<0,9 are partially transformable configurations. More than 80% of materials are recovered for up-cycling and reuse after they have served their functions

The advantages of transformable structures based on the high disassembly potential of building materials, elements and components results in a 0,6<TC>0,9 as shown in Table 8.1

building levels / advantages	disassembly on building level	disassembly on system level	disassembly on component level
adaptability of space lay-out	■		
adaptability of space functionality	■	■	
adaptability of system		■	
adaptability of component			■
reuse of system	■	■	
reuse of component		■	
reuse of element			■
recycling	■	■	■
variation	■	■	■

Table 8.1: advantages of transformable structures

The advantage of transformable systems with respect to environmental pressure grows with the increase of the changing sequences of their components. The main advantage of the transformable structures is in a reuse of parts whose functional use life cycle is shorter than their technical life cycle. Using the example of three wall systems (see Chapter 6) it has been calculated that a transformable wall made of demountable components, which is replaced seven times (during its total life) has a TC (index)=0,92 and saves 4776 tonne/year of raw material and provide a waste reduction of 5292 tonne/year compared to a conventional wall whose TC (index)=0,2. This results in the reduction of the yearly CO2 emission of about 18536 tonne /year (EET report 2004)

By providing an assessment of a building /system transformation, this research contributes to a better understanding of the impact that different types of building configurations have on the environment. It highlights aspects of building transformation that have a direct influence on the environmental efficiency of buildings and suggests a different design approach, which can reduce the negative environmental impact of buildings.

8.2 THE APPLICATION OF THE MODEL

The method presented in this thesis is in a way an eye–opener for the architectural engineering community. DfD has been widely utilised in the design of electronic products and for consumer goods. It is seen as a key element of environmental design. However, in building design it is still at the very beginning of its implementation.

This research has the potential for the successful implementation of sustainable building design, system and component development, environmental studies, and building management studies.

This method has been applied to two different research problems. One application relates to the market potential of housing for two housing corporations (Rondom Wonen, Pijnacker and Het Osten, Amsterdam). In the first case, the research deals with the transformation potential of apartments, and in the second with the improvements to TC.

The housing corporation explained that assessment of the TC of old apartments provides an objective analysis and helps them in their decision making process as to whether existing stock has the potential for future use or not. TC analysis in the second case results in the proposal of different strategies to increase the transformation potential of apartment blocks.
Another application of the method is the development of a flexible infill system designed in collaboration with Polynorm and Corus. The method is used as a decision support tool and an indicator of the environmental impact of the designed solutions. The results of this research could be used as:

- Guidelines for development of flexible systems;
- Guidelines for design of transformable buildings;
- As a tool to indicate environmental efficiency of flexible building assemblies;
- As an indicator of the flexibility of structures;
- As an educational tool that helps students get a better understanding of the technical composition of buildings and interdependencies between different design decisions during the design of building/systems configurations.

8.3 RECOMMENDATIONS

Taking into account the impact that building structures can have on society and the quality of life, one of the key indicators of the quality of the building in future will be a building's capacity to transform on all material levels. This capacity defines a building and system's flexibility, which allows their users to adapt them to their needs while reducing additional investment costs, and to the recovery potential of materials, which reduces the negative environmental impact of structures and reduces the investment costs in new materials.
The main indicator of such capacity is the disassembly potential of structural materials. To implement a strategy of transformable structures one can think of the TC index that will be required to obtain a building permit. Just as the owners of cars that pollute more have to pay higher taxes, developers of new buildings could be exposed to additional costs for obtaining a building permit, if the structure has little disassembly potential and consequently low TC.

8.4 FURTHER RESEARCH

This research opens many questions for the further research. Some possible research directions are listed below:

- Formalisation of a knowledge model calculation and its relation to a model that calculates environmental impacts.
- Integration of the model calculations with models that calculate economic factors.
- Formalisation of the relation between configuration typologies and use scenarios, which define which building configurations best fit a specific use strategy for a building.
- A knowledge model improvement with a greater number of practical cases.
- Analysis of the possibilities and limitations of different material groups with regard to DfD, and consequently TC.
- Integration of the DfD aspects into a CAD system in order to use it as a design support tool.
- Development of a sustainability index based on TC.

SUMMARY

Building Transforms
Acceleration of change in use and increase of environmental consciousness impose new construction, operating, and developing patterns on the built environment.

Due to the increasing dynamics within societies and current building methods, the physical impact of growing building activity within industrialised nations and developing countries becomes undeniable in the 21st century. This impact is measured mainly by increases in material use, CO2 emissions, investment costs, and quality of life expectations.

It is recognised worldwide that building demolition processes account largely for the negative impact of building structures on the built environment, and that disassembly could eliminate this negative effect. This research proposes that in order to bridge the gap between demolition and disassembly, it is necessary to change perceptions regarding the performance and technical composition of buildings and their products. In order to achieve this, disassembly should be possible on all levels of building, from the spatial to the material levels.

Dismountable structures introduce a three-dimensional transformational concept to building design that takes care of material recovery during space transformation, system/component reconfiguration/reuse during structural transformation, and material up cycling during material transformation. Such transformable structures could achieve more with less. In other words, better performance using fewer resources. This makes them essential to the global sustainability concept.
However, the present state of the technical composition of building structures forms the main obstacle to such a transformational concept. Research points out that the key to sustainable, green building engineering involves finding an alternative to the design and construction of currently highly inefficient static structures, which rely primarily on consumption of resources without any feedback loops. In that respect the Design for Disassembly (DfD) approach to the design of transformable structures presented in this research, has been defined as a breakthrough in conventional thinking about the use and performance of building structures.

Summery of the scope and results

The aim of this research was to set the guidelines and define a conceptual framework for the sustainable, green engineering in building design and construction. This has been achieved by defining design aspects of transformable structures, according to which the disassembly potential of buildings and their systems can be optimised and evaluated. In order to achieve this, the following methods have been applied:

- Analysis of functional, technical, and physical composition of building and systems configurations (which are the indicators of configuration performance with respect to disassembly)
- Analysis of DfD approaches in product industries
- Analysis of the dynamics of change in buildings and its systems, which indicates when and where disassembly takes place.

The results of this analysis can be summarised as follows:

- An understanding of the impact that design decisions regarding technical composition have on the behaviour of the building/system configuration during transformational processes.
- Development of a knowledge model for the assessment of Transformation Capacity (TC) based on the disassembly potential of structures
- Understanding the relation between TC and environmental efficiency of buildings
- Provision of a design framework and guidelines for design of transformable systems and buildings.

SAMENVATTING

De groeiende bouwactiviteiten van zowel de geïndustrialiseerde landen alsook die van de ontwikkelingslanden in de eenentwintigste eeuw hebben hun gevolgen. Dit wordt vooral gemeten door de toename van materiaalgebruik, CO_2 uitstoot, investeringskosten, de kwaliteit van het leven en de levensduurverwachtingen.

De sloop van gebouwen belast de gebouwde omgeving en het milieu. Demontage kan dit voorkomen. Dit onderzoek doet voorstellen het hiaat tussen sloop en demontage te overbruggen. Daartoe moeten de opvattingen over prestatie en technische samenstelling van gebouwen en bouwproducten worden herzien: Demontage moet mogelijk zijn op alle bouwniveaus, zowel qua ruimte als materiaal.

Een driedimensionaal transformatieconcept van demontabele gebouwen draagt zorg voor het terugwinnen van materiaal tijdens ruimtelijke transformaties, voor het re - configureren dan wel hergebruiken van bouwsystemen en componenten tijdens transformatie van bouw constructies en transformatie van materialen. Dergelijke transformeerbare veranderbare structuren kunnen meer bereiken met inzet van minder, hetgeen wezenlijk is voor een universeel duurzaamheidconcept. Echter, de huidige bouwpraktijk staat dit transformatieconcept in de weg. Om duurzaam te kunnen bouwen moet een alternatief gevonden worden voor bestaande inefficiënte en statische bouw structuren, moeilijk te veranderen gebouwen en verbruiken in plaats van hergebruiken van grondstoffen. Dit onderzoek beschrijft Ontwerpen voor Deconstrueren (DfD, Design for Deconstruction) en doorbreekt het conventionele denken over gebruik en prestatie van de gebouwde omgeving.

Samenvatting van de reikwijdte en de resultaten

Dit onderzoek biedt richtlijnen en definities voor een conceptueel kader voor een duurzaam en ‘groen’ gebouwontwerp en technische uitwerking. Bouwdelen zijn gedefinieerd als transformeerbare structuren. Dit vergemakkelijkt demontage van

gebouwen en hun systemen en kan vervolgens worden geoptimaliseerd en geëvalueerd. Hiertoe zijn de volgende werkwijzen toegepast.
- analyse van de functionele, technische en materiele compositie van gebouwen en systeemsamenstellingen (dit zijn indicators voor de mogelijkheden van montage en demontage).
- Analyse van DfD bij de fabricage van producten.
- Analyse van de dynamiek van gebouwen en systemen. Dit geeft aan wanneer en waar demontage plaats kan vinden.

De resultaten van deze analyse kunnen als volgt worden samengevat.
- Een begrip van ontwerpbeslissingen in zake de technische samenstelling; een begrip van het gedrag van het gebouw/ systeem gedurende de transformatieprocessen.
- Ontwikkeling van een kennismodel voor de beoordeling van de Transformatie Capaciteit (TC), gebaseerd op de demontagemogelijkheden van bouw constructies .
- Inzicht in de relatie tussen TC en de milieueffectiviteit van gebouwen.
- Een ontwerpkader en richtlijnen voor het ontwerpen van veranderbare systemen en gebouwen.

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