W. Debacker et al., International Journal of Ecodynamics. Vol. 2, No. 4 (2007) 258–277

# FOUR-DIMENSIONAL DESIGN: FROM STRATEGIES TO CASES – GENERATION OF FRACTAL GRAMMAR FOR REUSING BUILDING ELEMENTS

W. DEBACKER[1], C. HENROTAY[2], A. PADUART[2], S. ELSEN[2], W.P. DE WILDE[1] & H. HENDRICKX[2]
[1]Department of Mechanics of Materials and Constructions, Vrije Universiteit Brussel, Belgium.
[2]Department of Architecture, Vrije Universiteit Brussel, Belgium.

ABSTRACT

Because of its scale and the role it plays in our lives, a healthy built environment is of vital importance. As a part of material culture, buildings have to support human needs. But because of their static nature, obtained through design, most contemporary buildings and their components have a negative impact on their surroundings. The huge quantities of waste produced during demolition and the still rising emission of greenhouse gases created during use of the building, manufacture and waste treatment of its components are environmental indicators of an inefficient and unhealthy design. Moreover, a socio-economic paradox has been created. Due to inadequate design many buildings are unable to adapt to (fast-changing) contemporary requirements. As a result many constructions are left to their fate and decay. This inefficient use of matter and space is in sharp contrast with a global need for affordable housing. In high density countries, such as Belgium, building plots are scarce and expensive. In addition to this, the UN Human Settlements Programme (UN-HABITAT) estimates that 600 million urban residents and 1 billion rural dwellers in developing countries live in inadequate housing. In this paper, three main methods that integrate the fourth dimension, i.e. time, into design are described: design for adaptability (construction reuse), design for deconstruction (component reuse) and design for dismantling (material reuse). These four-dimensional design strategies strive for a healthy built environment, by taking into account, as from the first sketches, the wear and tear of artefacts and the changing and evolving circumstances that will affect them. The design of several construction kits, developed at the Vrije Universiteit Brussel, shows that the designer must pay attention to detailing. The key detailing principles and two design cases are further examined in this paper.

*Keywords: adaptability, conservation of resources, deconstruction, design cases, detailing principles, dismantling, fractal geometry, reuse of building elements.*

## 1 INTRODUCTION

As an important part of the material culture, the built environment is a main contributor to the industrial way of living. Because of the great amount of material and energy needed (human as well as mechanical), the built environment is responsible for its share of environmental and socio-economic impacts.

### 1.1 Environmental impact of the built environment

*Quantity of waste* is defined by the European Environment Agency (EEA) as an indicator of the material efficiency of society, since excessive waste represents an enormous loss of resources in the form of materials and energy [1]. Excessive quantities of waste can result from inefficient production processes, poor durability of goods, excessive consumption patterns, and also due to short-term, inadequate design.

In the period 1998–2002, the total waste generation in the European Union was about 1,400 million tons per year. Construction, demolition and manufacturing industries generate 45% of the total waste [1, 2].


ISSN: 1743-5242 (paper format), ISSN: 1743-5250 (online), http://journals.witpress.com
DOI: 10.2495/ECO-V2-N4-258-277

Although it is losing margin to the transport sector (21%), energy production and supply in the built environment is the largest sector contributing to the *emission of greenhouse gases*. About 38% of total EU-15 greenhouse gas emissions (mainly $CO_2$) in 2004 originate from energy production and the use of electricity and heating in households and buildings for commercial and institutional purposes. A survey by EEA showed a decoupling of $CO_2$ emissions and electricity consumption and production in EU-15 between 1990 and 2004. While electricity and heat production rose spectacularly in that period, the total $CO_2$ emissions remained more or less the same. Increases in population and household size had only a small rising effect on the total $CO_2$ emissions. On the other hand, the combustion efficiency improvements, better insulation, the extended use of district heating and the shift from coal to gas decreased $CO_2$ emissions from households and services [3].

Contemporary research and policies focus their attention on the decrease of energy during use or operation of buildings. Appropriate environment-friendly design – and subsidising it – makes the construction of low-consumption and self-sufficient solar buildings in many European countries possible [4]. With an ever-growing population and a popular Western way of consumption, other steps have to be undertaken to lower the environmental pressure. First, every stakeholder has to be sensitised and supported to construct and use buildings with a positive rather than a negative impact on the environment. Consumption (behaviour) must change. This is not only a design issue but also involves an educational programme.

Lowering the impact of operation means that the other phases in the building's life will need equal or more attention. Studies on low-consumption dwellings have shown that the production energy can account for 40%–60% of the total energy [5]. Manufacturing and waste management will need to be reviewed to lower their role in the depletion of raw materials and emission of greenhouse gases.

### 1.2 Socio-economic impact of the built environment

The biggest part of the built environment is *housing*. Globally speaking, many cultural and individual interpretations are given to the word 'housing'. For some it is a shelter against human or natural hostilities, or merely a place to sleep or rest; for others it is a status symbol. While UN and non-governmental organisations consider housing a basic right, adequate accommodation is still unaffordable for a large part of the world population. The UN Human Settlements Programme (UN-HABITAT) estimates that 600 million urban residents and 1 billion rural dwellers in developing countries live in inadequate housing [6, 7]. The main cause for this may be attributed to poverty. The increasing amount of natural and man-made disasters [8] results in important material and economic losses, including housing. Most countries affected by natural or conflict-based disasters are developing countries facing important socio-economic problems. Consequently, managing the huge need for shelter and reconstruction is a challenging task. Due to the close relation between poverty, vulnerability and disasters, the losses faced by developing countries are also much higher than the losses faced by a developed country after a disaster. Therefore, the need for material solutions supporting sustainable development is vital [9].

In many European countries too *affordable* and *adequate housing* are hot topics. High-density countries such as Belgium and the Netherlands can be considered as an extensive built-on region, where building plots are scarce and expensive. Paradoxically, many existing (social) dwellings do not meet the changing demand. The Flemish government discerns three major trends over the past decades: an increasing demographic ageing, a rising migration and a general reduction of family sizes [9]. Combining these social evolutions with rapid technical progress and changing building and living trends, many habitats (and public buildings) do not meet the contemporary living and safety requirements anymore. This leads to dilapidation and waste of land and matter. These dwellings – like most buildings in our Western society – are designed in terms of *end states*; the moment the first sketches are drawn, the construction's finality is planned or completely denied. Because of their static nature they are not suited to meet the demands of a quickly changing society. Many building components are consequently condemned to end on the waste pile or are brought back into circulation by means of expensive and consuming industrial processes.

All regional governments in Belgium have decided to reinstate the exploitable (social) dwellings and to build new ones [10, 11]. This big-scale reconditioning will be a long-lasting operation; it will be unmanageable if it is supported by traditional, static design concepts. Building and living requirements will always change. Thus, our buildings have to evolve with them. Hence, a *healthy* built environment requires *a dynamic concept*; a step-by-step redesign process of gradual changes in which no end states or final goals can be defined.

## 2 TEMPORARY CHARACTER OF CONSTRUCTIONS

### 2.1 A complete life cycle model

The awareness of the limited lifetime of our heritage is ever increasing; slums are demolished, old train stations are replaced by prestigious ones, offices are refurbished and monuments and heritage buildings are carefully renovated or are the object of restoration. Still designers, professional developers and real estate owners pay little attention to the temporary character of a construction: even during the study and the drawing phase this aspect is often forgotten or even simply ignored. Facing changing uses during the lifetime of the construction, static solutions will make transformations extremely difficult – if not impossible. It could happen that some structural elements still perform in a satisfactory way, but the owner will often prefer to demolish. This causes a lot of debris. In a few words: the actual society is missing a dynamic design approach, allowing transformations and adaptations during the life cycle of a construction.

Figure 1 shows a commonly used model which describes the cradle-to-grave life cycle of building materials in a typical Western building environment. Material and energy input is needed to extract raw materials, to process them into construction elements and to assemble them into a qualitative building. When the building does not meet the contemporary requirements (of individuals and society) anymore, it is more often than not demolished and reduced to waste.

Although this model explains the contemporary waste and energy policy, it is a reduced form of a bigger and more complex model wherein more flows are integrated. In fact, in the contemporary built environment (excluding urbanism) three life cycles can be discerned: the cycle of the *building*, the cycle of its *components* and the cycle of the *materials* used to manufacture the components. Even though these three cycles become one during the use of the building, this is not the case before construction and after dismantling. For a total picture of the material and energy flow (and their side effects) it is thus important to take into account all three cycles.

After the use of a construction, various management choices which affect the total energy, cost input and material flow are offered. Typically seven different 'paths' can be followed [12]. In two of these, the building remains standing (paths VI and VII); in the other five cases the building is partially or totally disassembled or demolished. After sorting (on the disassembly site or on the selection site) the building components and/or materials are taken out of the cycle(s) (paths I and II) or a second life is offered (paths III, IV and V). All seven possibilities are defined below.

*Path I – Land filling:* All or a part of the sorted components is disposed by burying it. No saving on the total energy input can be considered. Moreover energy has to be taken into account to transport

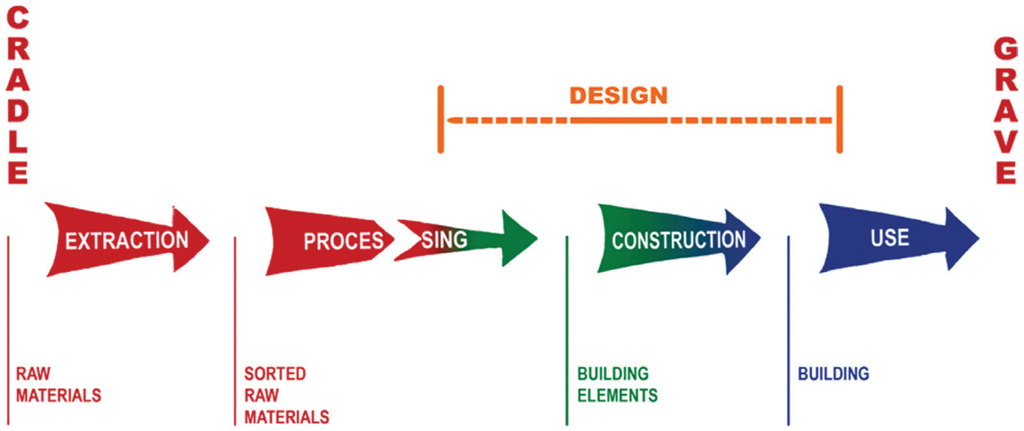


Figure 1: Linear model to describe the flow of materials used in the built environment.

the waste to the disposal site and to bury it. Most common side effects of inorganic components are erosion and pollution of air, water and soil. In contrast, the disposal of some biodegradable construction elements or materials can nourish the site instead of damaging it. McDonough and Braungart [13] promote natural disintegration of waste through the use of a design approach wherein biodegradable components and technological (i.e. non-biodegradable) components can easily be separated. In the long run, the assimilation of biodegradable components by nature could offer new organic material for production (path $I_{bis}$).

*Path II – Combustion:* All or a part of the sorted components is burned. Material is permanently taken out of the cycle(s) in the form of small particles and greenhouse gas emissions. Thanks to the exothermic process energy can be recovered in the form of heating.

*Path III – Feedstock recycling:* This type of recycling refers to a process where the sorted components are reprocessed into raw materials or 'feedstock' to make building material(s). For example, a glass bottle can be recycled for aggregate. Still a high amount of energy is needed to reintroduce the material into the cycle. The emission of greenhouse gases has to be considered.

*Path IV – Material recycling:* During this process separated components are directly reprocessed into building material(s). For example, a glass bottle can be recycled as glass. Still a high amount of energy is needed to reintroduce the material into the cycle. The emission of greenhouse gases has to be considered.

*Path V – Reuse of components:* Here, sorted elements are, after a maintenance procedure, 'recycled' into the same components for similar or other purposes. For example, a glass bottle can be reused as a glass bottle after washing it. If maintenance procedures are too labour-intensive and/or too costly another path is recommended.

*Path VI – Renovation or restoration of the building:* Although the building can be partially demolished or dismantled, a part of it remains. External and/or internal additions to the existing building are performed through implementation of new building elements. The reinstated artefact can fulfil the same or another function. Since most buildings are not designed to be easily restored, it is often a costly operation involving necessary expertise.

*Path VII – Reuse of the building:* The building stays the same. Only minor maintenance is needed to extend its use. The reinstated building can fulfil the same or another function. Spaces which have a versatile or flexible character facilitate functional changes.

Although the numbering of the paths gives a broad idea of the decreasing impact of end-of-life solutions on the depletion of material resources and waste accumulation, this list should not be viewed as a fixed hierarchical approach. Similar to the Delft Ladder [14], named after the university where it was developed, it is a flexible approach where in most cases paths can be combined extensively. The seven flows are shown in the life cycle models below (Fig. 2).

It is essential to acknowledge the importance of appropriate design. To create a 'healthy' built environment, its material components have to support this. Buildings, their components and materials have to be designed and chosen to be in a continuous life stream as effectively as possible. In this line of thinking integral life cycle analysis and life cycle cost analysis can provide the necessary information to make qualitative (re)design and management decisions. Complete life cycle models are thus indispensable tools to accomplish this.

## 3 DEFINING FOUR-DIMENSIONAL DESIGN

According to the line of reasoning developed in Sections 1 and 2, it can be stated that 'design for (qualitative) use of a construction' is not enough. A short-term and partial view on the construction environment must be complemented by a long-term and holistic view.

Four-dimensional (4D) design refers to an attitude of the designer, using his talent and horizontal knowledge to provide an artefact with a (more) sustainable character. This has to be done by integrating the fourth dimension, i.e. *time*, in the first stages of conception. Time is not only related to the wear and tear of the artefact, but also to changing and evolving circumstances which will affect it. In this sense, the artefact and its components must have the potential to adapt to these sometimes unexpected changes. Consequently, a 4D designer considers an artefact as a materialised answer to a process of changing events. Even when the designer cannot predict with great certainty how governing circumstances will evolve, the artefact may not be a static result of a preprogrammed end state. Four-dimensional design can be taken into account by closing the three mentioned life cycles – material, component and artefact – in an effective way. For the built environment te Dorsthorst and Kowalczyk propose three design strategies, namely [14]:

1. *Design for dismantling*, wherein *building materials* should be (technically) easy to separate. After selection, technical materials can either be recycled as feedstock (path III) or as material (path IV). If possible, down cycling wherein the initial material is used for a lower grade function must be avoided. Biodegradable materials can be brought back into the natural cycle (path $I_{bis}$).
2. *Design for deconstruction*, wherein *building components* should be (technically) easy to disassemble. To reuse building elements (path V) several times, they must be designed in such a way that during handling damage is prevented as much as possible. Before reintroducing the elements back into the component cycle, labour moderate and cheap maintenance procedures should be undergone, if needed.
3. *Design for adaptability*, wherein *buildings* should be (technically) easy to adapt to changing constraints. During design or re-design of a building it should be conceived to be flexible and versatile (path VII) and/or undergo labour moderate and cheap refurbishment procedures (path VI). (Adaptive) building reuse (path VII), wherein the initial building can be reused for the same or another function is preferred.

These three 4D design strategies can be used in a complementary way. The reader must not confuse 'design for deconstruction' with the architectural paradigm 'Deconstructivism', wherein the aim is to design without any contextual reference. Buildings designed by deconstructivist architects, such as

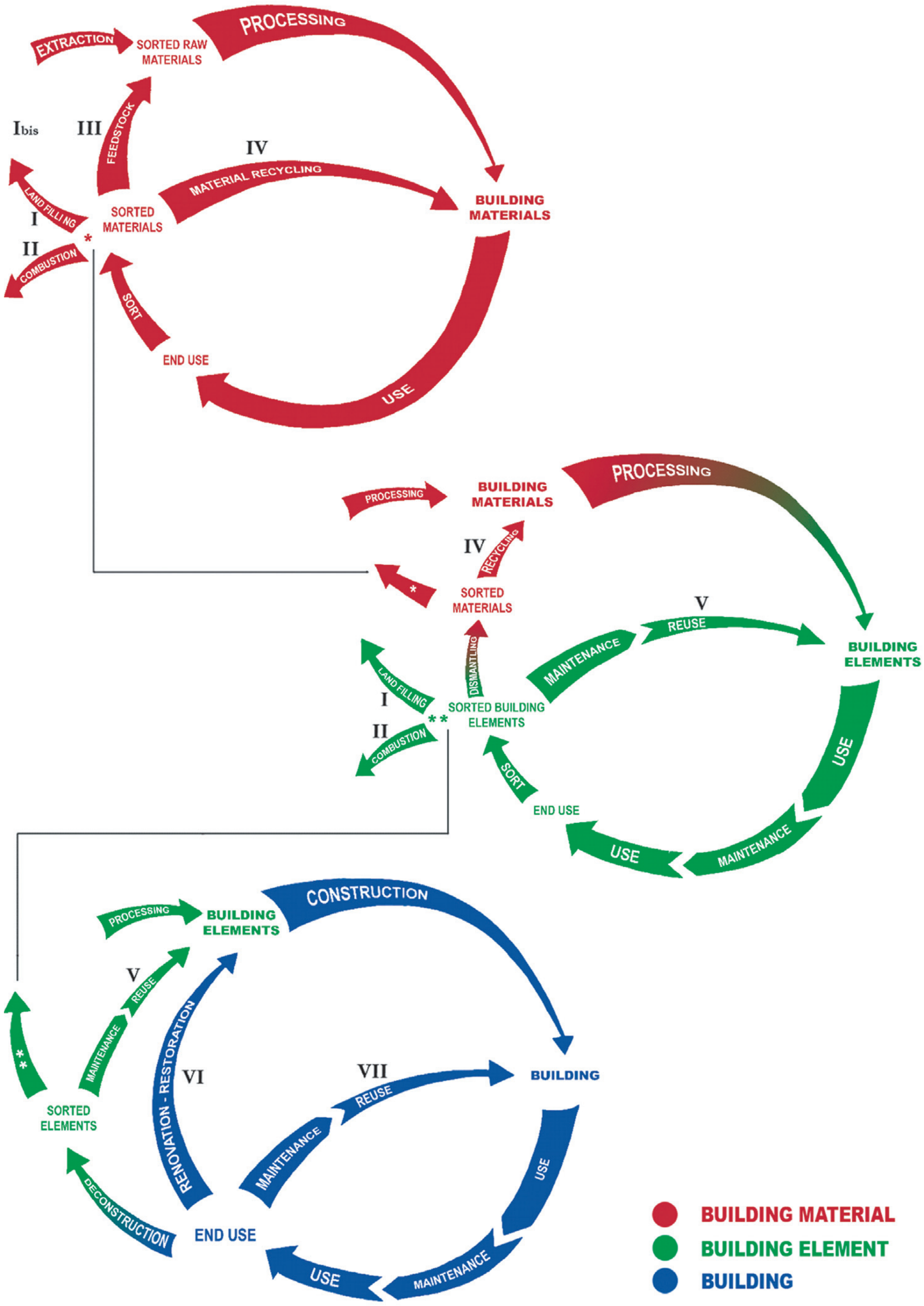


Figure 2: Life cycle model of building materials (above), building elements (middle) and buildings (bottom).

P. Eisenmann, D. Liebeskind, Z. Hadid and B. Tschumi, show no contextual reference with any other building or anything else; these are often characterised by unbalanced and chaotic forms, defying the basic natural laws.

Of the described flows in Fig. 2, two of them are – for the time being – only used sporadically in the Western built environment: the concept of naturally disintegrating biodegradable materials (path $I_{bis}$) and the 'reuse of components' principle (path V). Yet, both of them show a lot of potential. If used properly, the cycle of building material and component are carried out with a positive impact on the natural environment and a low life cycle cost. McDonough and Braungart have shown that natural disintegration of biodegradable materials is perfectly applicable when an artefact is designed to be dismantled, instead of demolished, and the biodegradable components can be separated from the technological ones [13, 15, 16]. Compatible to this, a 4D design approach can be used to design construction elements that can be further deconstructed into (dimensionally and formally) compatible basic elements (biodegradable or not), which can eventually be reused as parts of other building components. In Section 4 such a design approach is further detailed.

## 4 HENDRICKX–VANWALLEGHEM DESIGN APPROACH

Hendrickx and Vanwalleghem invented a design approach that includes a dynamic view on the built environment [17]. It encloses guidelines to design multiple construction systems, all compatible with each other, by which a variety of adaptable and reusable construction elements can be composed. Each construction system is made of a minimum number of basic elements and a set of combination rules. They allow the conversion of each artefact into a different configuration, by means of adding, removing or transforming the basic elements which it is made of. It offers a high potential of recycling and (direct) reuse. The outcome can be compared with the 'Meccano' building set, which, in this view, encloses all materials and techniques, and is applicable to all scales.

Following this 4D design approach structural and non-structural building components should be further decomposed into *compatible basic elements*. These can be compared to the letters of an alphabet: they do not carry any semantic meaning. The basic elements can be combined in different ways to form a variety of construction elements, which in the actual comparison can be considered as words. Three types of basic elements can be discerned:

- *line elements* (one-dimensional),
- *plane elements* (two-dimensional),
- *volume elements* (three-dimensional).

*Point elements* (zero-dimensional) can be categorised in the previous classification: e.g. bolts can be considered as scaled volume elements.

A *construction kit* is defined as a grouping of a *few* basic elements aiming at the assembly of one or more (adaptable) components or constructions. Attention must be drawn to the fact that the assembly of a complete building will very often require several construction kits. It is thus absolutely necessary that all basic elements found in the same construction kit, or even another one, be compatible with each other. The establishment of explicit standardisation rules is therefore stringent.

### 4.1 Design of construction systems

#### 4.1.1 Design tool 1: a generating form and dimensioning system

Using their own developed design tool called a *generating form and dimensioning system*, Hendrickx and Vanwalleghem proposed a set of standardisation rules. It is a central concept in the design approach, in the sense that it ensures full compatibility of form and dimensions between all basic elements.

Hendrickx and Vanwalleghem presume that any tangible basic element, in any construction phase, can be approximated with a minimal diversity of basic forms. They have chosen the *square*, its *diagonals* and the *inscribed circle*, due to an important property of the former, i.e. its orthogonality. This makes sense since right angles are found in many material solutions and certainly in the area of construction.

To make effective use of the proposed system, the set of basic forms should be provided with basic dimensions. In order to achieve optimal flexibility and combination, the basic elements should have the same dimensions. Because dimensional differences will be unavoidable, Hendrickx and Vanwalleghem propose to solve the problem using the rules of either *halving* or *doubling*. Both are the result of an easy mathematical function and create a geometrical series. Starting with a square of side $x$ one finds: $x$, $2x$, $4x$, $8x$, … . A more general approach is to include the length of the 45° diagonals by choosing the operator 'multiply or divide' by '$\sqrt{2}$': $x$, $\sqrt{2}x$, $2x$, $2\sqrt{2}x$, $4x$, $4\sqrt{2}x$, $8x$, … . Series of a lower standardisation level are set up by adding up values of the primary series. The *fractal model* in Fig. 3 can be projected on all materials and all scales and can therefore define the basic elements for different material types.

Grouping *all* possible variations within a chosen set of basic elements is defined as a *construction system*. The types of basic elements (first-order elements) are defined by both their form and their constitutive material, as these define how basic elements should be joined and combined into building

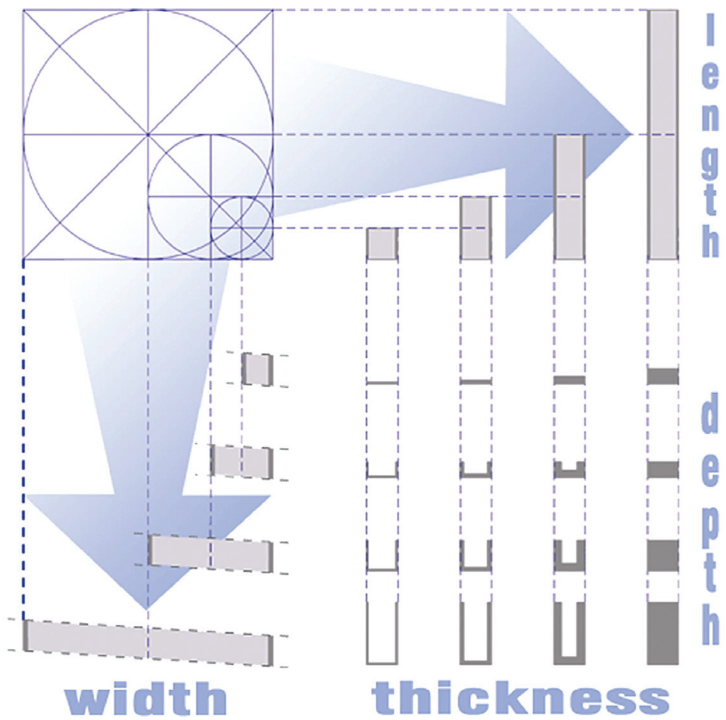


Figure 3: Designing basic elements through a fractal model of the generating system.

components (or basic elements of another level). Here, attention should be drawn to the fact that a construction system is not an object, but rather a set of entities, i.e. smallest elements of the system, between which predefined relations exist. Among these are the dimensional and formal rules imposed by the generating system. The concept of *construction kit'* can thus be redefined as a rational selection of *some* basic elements out of one or more construction systems. The objective is to generate one or more flexible constructions and their constitutive parts.

4.1.2 Design tool 2: theoretical design catalogues

An aid to the development of construction systems is achieved by developing *theoretical design catalogues*. This development is carried out in the following way.

In the first step, each material solution, or more precisely each of its construction elements, in any phase, is objectively and verbally described, based on characteristics, strengths and weaknesses. Each characteristic has one or more parameters as a counterpart, all bracketed between predefined limits. This delimitation, for each parameter, is done at the level of the *entities*. Considering that all artefacts are measurable and can be depicted, most of the parameters can be visualised with simple symbols or pictograms and be categorised in different series. If a graphic representation is not wanted or impossible, a short verbal description will be sufficient. Through interpolation and/or a combination of the outer elements in the series all variants can be achieved. This can be illustrated with a simple construction element. The bearing capacity of a steel corrugated plate, subject to transverse loads – e.g. used as a roof element – can be described by three parameters: *its thickness*, *the number of waves per unit length* and *the height of the waves* (or also the predefined form of the wave) (Fig. 4).

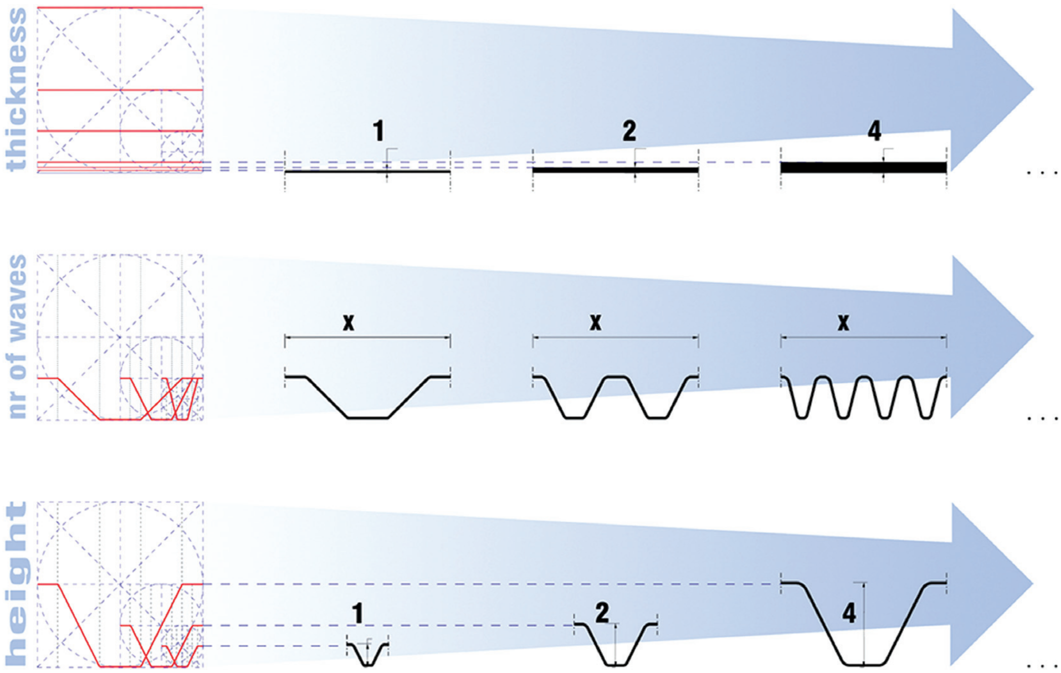


Figure 4: Theoretical design catalogue of a load bearing corrugated plate.

These parameters can be entered into a series by defining the extreme values. A thin plate is the opposite of a thick one: this means that there is a limit for the ratio thickness/span. The number of waves per unit length and the height of the waves are limited by plate thickness and fabrication process. All variants should lie between the defined limits.

Using arithmetic and geometric calculation rules, changes in each series can be described; every value of the parameter thus gets its place within the series. To achieve the goal of using a minimal number of basic elements, stepwise variations in each series are preferred. The adopted geometrical standardisation corresponds with the fractal model in the generating system.

A theoretical design catalogue is thus established, combining and juxtaposing elements. The emphasis has been put on 'theoretical', as in practice not all combinations are possible or technically sound. This means that they are erased in a *practical* catalogue.

This approach can be applied to a whole construction. As the bracketing of an entire construction is difficult, preference is given to deconstructing it into physically and non-physically observable elements, without forgetting to keep in mind the global context. For example, the maximum height of a building is often defined through ridge height or roof slope of adjacent constructions. The concluding result is a fan of design catalogues, each based on combinations of selected parametric rules. They allow to describe an (adaptable) artefact, existing or not, through translation of one or more series.

### 4.2 Modular and generating systems

The main asset of a modular construction system is an economical one. Thanks to (modular) standardisation, simplified and cheaper prefabrication processes are made possible, which consequently speed up the construction phase. Modular construction systems are also known to be flexible. However, this is not without any shortcomings. Changing the characteristics of a module or unit is excluded, because it has been technically and structurally denied. Adaptability – and by this the designer's freedom – is therefore limited to the addition and reduction of fixed modules. A commonly employed unit is *the foot* (in the horizontal plane). This unit is ≈30 cm and is rightfully successful as a functional, ergonomic and spatial unit. But it cannot be used at all levels of the design: for technical dimensions it is often too large and for structural purposes it is too small. A multi-modular grid provides an improvement, i.e. a superposition of modular design grids with a different module – related to the respective design level (structural, spatial, functional or technical). Design at different levels is thus possible, but not without potential conflicts. Using an arbitrary or inconsistent proportion between the module sizes, dimensional problems occur where different grid lines intersect [18].

The standardisation rules of a generating system are based on a *fractal* model (Fig. 3). Thanks to a single operator (divide or multiply by 2 or $\sqrt{2}$), switching to different design levels is always possible without jeopardising compatibility between each basic element. A generating system thus allows the development of (multi-)modular systems, but with the additional property that they can be used on different design scales. Furthermore, it is not 'the module' which is standardised but the (dimensional) modifiable basic elements which it is composed of. The latter is the key difference with modular construction systems.

A number of proportion theories have been developed in the course of history. Like the Golden section (1:0.618) and the Pythagoras ratios (1:2, 1:3, 2:3, 3:4), most of them originate from a belief that certain numerical relationships manifest the harmonic structure of the universe [19, 20]. The ratio 1:2 used in the generating system explained above is one of the Pythagoras ratios. Nevertheless, it is important to mention that this ratio is only used to dimension basic elements in order to maximise the compatibility between them. Hence, the above-presented approach matches perfectly with the idea of *open industrialisation*, wherein a minimum of construction elements belonging to several construction systems and distributors, based on the same design rules, can be combined together to form multiple (adaptable) projects [18].

## 5 DETAILING PRINCIPLES

In the previous section, a 4D design approach was detailed. Dismantling building components into basic elements of single materials will facilitate selection procedures and thus the reprocessing of materials (design for dismantling). Building with Meccano-like construction kits will facilitate the adaptive reuse of the construction and by this lengthen its lifespan (design for adaptability). However, the single most important benefit of the Hendrickx–Vanwalleghem approach is the compatibility between each basic element in a construction kit, as a result of which building components or parts of it can be easily and effectively reused in the same or another construction (design for deconstruction). Designing for deconstruction will logically affect the way of detailing. Based on the authors' experience [11, 21, 22] and the literature available [23–26], a summary of the key detailing principles is given in Table 1. More detailed information can be found in the above-mentioned references. Some principles are further discussed in the following subsections.

### 5.1 Connections

The choice or design of connections is one of the most important aspects of designing for deconstruction. The type of connection between construction elements will determine whether or not deconstruction can be done successfully; i.e. if reuse is possible without damaging parts and handling is done easily, minimising the amount of specific tools.

According to Morgan and Stevenson [25] three ways of connecting can be discerned: *infilled*, *direct* and *indirect*. Infilled connecting, such as gluing and welding, makes it virtually impossible to

Table 1: Summary of key detailing principles for design for deconstruction.

| Detailing subject | Key principles | References |
|---|---|---|
| Connections | Use indirect connectors and dry-jointing | [23–25] |
| Durability | Lengthen the lifespan of building components by patchable detailing | [25] |
| Access | Place layers of elements with more frequent cycles close to the surface | [23–25, 27] |
| | Connections have to be at reach | |
| Handling | Design small and lightweight components in accordance with the necessary tolerances and play during assembly and deconstruction | [23, 25] |
| | Limit the amount of fixings | |
| | Avoid special dismantling tools | |
| Structure | Design bearing structures which can be strutted and adapted safely and easily | [24, 26] |
| Services | Minimise the amount of mechanical services | [24–26] |
| | Strategic routing with a minimum of interpenetration between other layers | |
| Materials | Choose materials which allow above-mentioned principles | [24–26] |

deconstruct, unless the filler is very soft, such as lime mortar. Direct connectors usually interlock or overlap with components, which can make deconstruction difficult due to the assembly process. Indirect connections are usually easier to deconstruct; they are interchangeable and independent from adjacent components. Furthermore, the last type of connection is preferred over the others, because of its reversibility and repeatability. In Table 2 typical connections used in the construction industry are evaluated.

When design for deconstruction is chosen, conceiving *dry joints* is a straightforward decision. Nevertheless, the designer must bear in mind that this decision will affect the global and local physics of the building. Attention must be drawn to thermal and acoustical leaks, and wind, air and water tightness. Detailing of demountable walls, floors and roofs can be completely different from detailing using permanent jointing (Section 5.2). Moreover, realistic tolerances and play between all elements must be taken into account, to allow movement during deconstruction and avoid unwanted stress accumulation due to thermal extension of different materials. The disassembly process may require greater tolerances than the manufacture process or the initial assembly process [28].

### 5.2 Accessibility and durability

Different parts of a building perform different functions and have different lifespans. Incremental refurbishment and upgrading processes often produce more waste than demolition of complete buildings [25, 27]. The generated waste is unnecessary since components are often not really damaged or because buildings are designed in such a way that not only the component itself but also several adjacent and connected elements have to be removed as well.

Dividing the building into *layers*, wherein each layer consists of elements with different lifespans, will lower waste during refurbishment and upgrading. Placing layers with more frequent replacement cycles closer to the surface will facilitate access. Non-structural components should also be constructed independently from structural elements – which have the longest lifespan – in such a way that safety is guaranteed during use and refurbishment of the building. According to Brand [27] a building can be seen in different functional layers as detailed in Table 3.

Layering does not mean that each element has to be mounted separately. To speed up site construction, structural elements, insulation, services and skins may be bonded together in single

Table 2: Comparative analysis of typical connections in the construction industry, based on ref. [25].

| | Type | Speed of construction | Strength of connection | Reuse of connection | Deconstruction potential |
|---|---|---|---|---|---|
| Mortar bonding | Infilled | – | – to + | – – to – | +/– |
| Adhesive bonding | Infilled | +/– | – to ++ | – – | – – |
| Welding | Infilled | +/– | ++ | – | – – |
| Resin bonding | Infilled | +/– | ++ | – | – – |
| Nail fixing | Direct | +/– | +/– | +/– | +/– |
| Riveted fixing | Direct | + | + | +/– | – |
| Bolt fixing | Indirect | + | + | ++ | + + |
| Screw fixing | Indirect | + | +/– | + | + |
| Friction | Indirect | + | – | + + | + + |

– –, none; –, limited; +/–, average; +, substantial; + +, extensive.

Table 3: Range of lifespans of typical layers in a building [27].

| Layer | Lifespan (years) |
|---|---|
| Site | |
| Structure | 30–300 |
| Skin | 20–60 |
| Services | 7–15 |
| Interior layout | 3–30 |
| Furniture and belongings | |

prefabricated pieces. However, the ability to deconstruct them into functional entities must be provided. Otherwise, the weakest link in the chain – the element with the shortest lifespan – will be the decisive factor for the replacement of the whole prefabricated part [25].

Too small elements will lengthen construction, deconstruction and dismantling. Large elements which are too heavy to be lifted by workers can cause problems when *access* by a crane is impossible. In this view, design for deconstruction should be completed with design for *lightweight components*. Optimal use of material in accordance with standardisation of elements should be taken into account. Several structural studies on steel skeletons [11] with the help of a generating system – used in the Hendrickx–Vanwalleghem approach – give a structural efficiency similar to standard profiles on the market.

Layering has a positive effect on the acoustics of lightweight constructions. The succession of layers with different material characteristics (density, stiffness and porosity) and thickness will insulate from airborne noise with different frequency ranges. As discussed earlier, (dry) joints and (indirect) connections are the weakest members to prevent acoustical and thermal leaks, as well as wind, air and water tightness. These matters should be treated with extra care during design, construction and refurbishment.

A fundamental constraint when reuse of components is taken into account is the *durability* of the components. Components – and basic elements – have to be durable enough to be repaired or reused with a minimal cost and labour. *Patchable detailing* allows elements such as doors, windows and walls to be easily maintained through partial rather than complete replacement [25]. The more robust the edges between connector and component, or basic element, the more likely they can be reused a maximum number of times. Dry-joint techniques that avoid excessive pressure are preferred, particularly if the fitting is simple.

Components which are not durable, and thus unlikely to be reused, should either be safely biodegradable or be easily recyclable (path $I_{bis}$, III or IV). Therefore, the component should be of a single material or quickly/easily dismantled into basic elements – and thus individual materials.

## 6 CASES

In the following subsections, two cases illustrate the possibilities created by the implementation of 4D design strategies and approaches.

### 6.1 Case 1: shelter after disasters

The increasing amount of natural disasters results in an important housing shortage. For example, in December 2004, 1.5 million people in southeast Asia lost their homes, and also their livelihoods, due to the tsunami disaster [29]. The recovery process consists of three main phases – ‘emergency’, ‘care and maintenance’ and ‘reconstruction’. In most cases, various approaches and material solutions are implemented during the subsequent stages of the relief intervention resulting in waste of material and financial means. In addition, too little attention is paid to the transition from emergency to reconstruction. Yet, due to landownership issues and the lack of means of local authorities, the reconstruction often takes more time than assumed. Consequently, the affected population has to face inadequate housing conditions for a period that can last a couple of years. To what extent 4D design can support the recovery process and offer a solution to the above-mentioned difficulties?

6.1.1 Design of an adaptable and versatile shelter kit

Based on the ‘design for deconstruction’ strategy and the approach proposed by Hendrickx and Vanwalleghem, an adaptable shelter kit has been developed at the Vrije Universiteit Brussel. The design relies on the creation of versatile and reversible connection elements for the cover as well as for the bearing structure [21, 30]. The elements of the shelter kit can be combined into various shelter typologies and sizes. Nevertheless, in order to enable quick and efficient relief immediately after the disaster, three *basic emergency shelters* – for two, four and six persons – based on the same basic elements can be provided to the affected population (Fig. 5). *Complementary layers*, e.g. mosquito nets, insulation, shading, can be added to adapt the shelters to the local climate. In a future time, the elements can be recombined with additional (local) materials into a more comfortable transitional shelter (Fig. 6) to support the livelihood of the inhabitants.

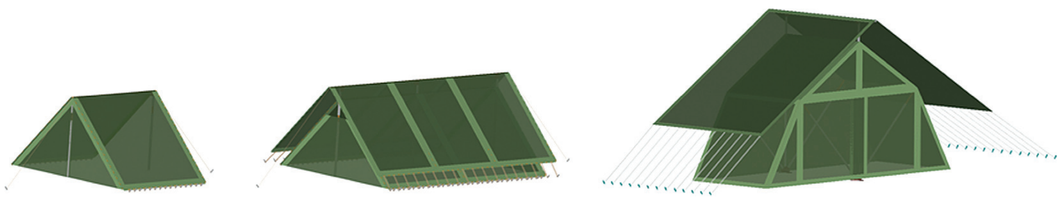

Figure 5: Basic shelter for two persons; for four persons with shading and ventilation opening and for six persons without ventilation opening.

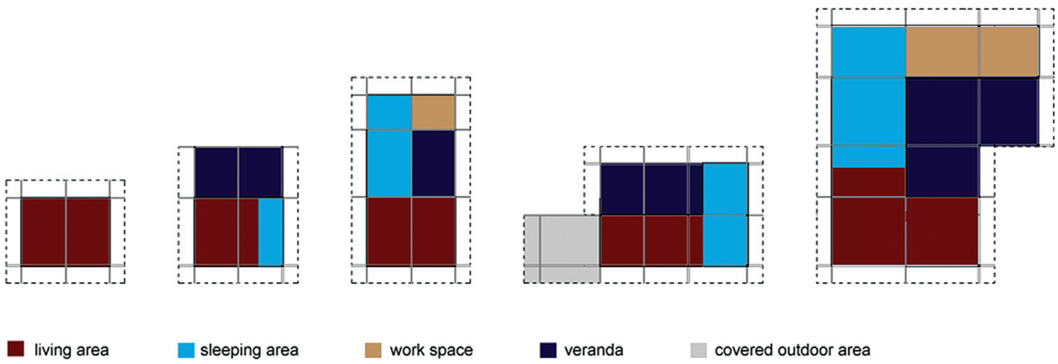


Figure 6: Altering plan configurations for transitional shelter starting from a basic transitional shelter for two persons to an upgraded shelter for seven persons.

With the view to investigate the feasibility of the shelter kit, a prototype – produced in cooperation with the Belgian Army – has been tested and evaluated by several target groups (army corps, NGOs, laymen, women and engineering students in architecture). *Workshops* were held during which the different groups assembled various typologies (Fig. 7). The workshops and the working of the prototype were evaluated based on questionnaires, recordings of the assembly times, observations and focus group interviews.

6.1.2 Results

The workshops and the tests performed on the prototype enable the investigation of difficulties and bottlenecks regarding the design and the assembly in order to optimise the proposed shelter kit. The primary goal of the construction kit – to provide shelter and protect the inhabitants from external factors – has been reached; the elements can be combined to provide different shelter typologies which endured water and wind testing. Nevertheless, important detailing difficulties were encountered. The aspiration for maximal adaptability of the construction system and versatility of the elements and components results in a complex and confusing system harming the ease and pace of construction. The lack of clarity is induced by the versatility and the huge amount of connection points and possible combinations. Confusion leads to many errors during the assembly, undermining the quality of the shelters. In addition, the number of connecting elements dramatically increases the mass of the cover, decreasing the ease of handling and transporting the elements.

The lessons learned point out the necessity for an equilibrium between adaptability on one hand and constructability on the other hand. The need for process based design should not harm the simplicity of use or the quality of the constructions.

6.2 Case 2: renovation of a high-rise building in Flanders

This case study regards a 4D designing approach applied to the renovation of the Chicago Building, a high-rise dwelling complex situated in Antwerp (Belgium), and demonstrates how a long-term

Figure 7: Different typologies assembled and tested during the workshops.

design approach can be implemented in existing buildings. The Chicago Building represents a large number of similar high-rise housing buildings in Flanders that were built to answer the rising prices of building plots in the 1970s and are now in urgent need of renovation. The building provides only two standard housing types for a wide range of users varying in family composition, age and cultural habits. As a result of the actual rigid conception of the building, efficient and adapted living is being obstructed.

Under the present circumstances, this lack of adaptability is often the major reason for the demolition of this type of building, contributing to the mentioned waste and energy issues. Bearing this in mind, a dynamic concept is being introduced in the renovation process, supporting the natural evolution of the resident's needs and taking reuse in consideration. Therefore, the original building is stripped down to the bearing structure, creating empty *plots*, as a support for the 'infill' of various housing types. This design interconnects adjacent plots through the introduction of supplementary openings in the bearing walls. Other building plots can be achieved, allowing houses to expand or contract to neighbouring plots when changes occur in the socio-economical situation of the inhabitants. To allow various scenarios occurring in living processes, the proposed construction kit for the infill of the building takes adaptability, dismantling and deconstruction into account from the earliest stages of design.

#### 6.2.1 Design of an adaptable renovation kit [31]

Through a separation of *support* (including the collective facilities) and *infill*, different layers are being created: the bearing structure, vertical circulation facilities (stairs, elevators), technical facilities, public spaces and the dwelling facilities. This kind of layering makes it possible for the different participants of the building to intervene in specific construction levels, without influencing the functioning of other layers (Fig. 8).

The main construction kit, used for adaptable dwellings, consists of three kinds of basic elements: steel profiles (line elements), insulation and covering panels (plane elements), and corner elements that enable the assembly of a three-dimensional frame structure (Fig. 9). All seams are achieved by means of dry jointing and indirect connections (bolts) with integrated tolerances. To prevent technical services from restricting the realised housing flexibility, supply of electricity, water and heating is clustered in standard units. Several service units are provided on every minimal plot and support easy plug-in connections for the dwellers' necessary technical facilities.

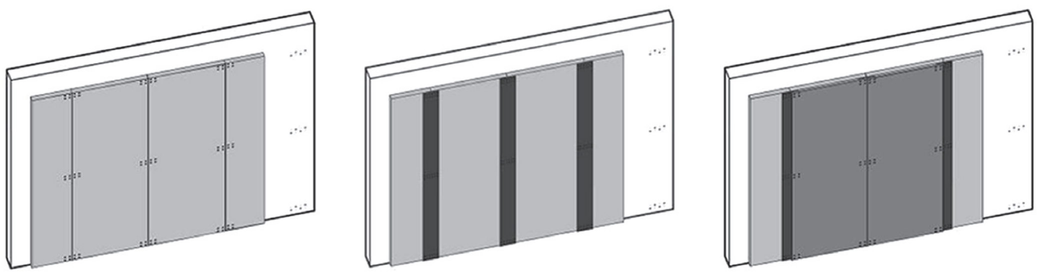

Figure 8: Stepwise construction of infill walls [31].

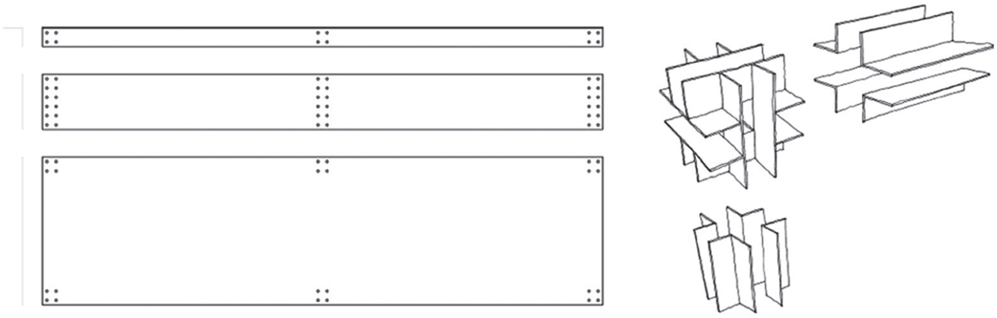

Figure 9: Basic elements of the renovation kit [31].

Figure 10: Adaptive reuse of the Chicago Building: three possible dwelling configurations [31].

6.2.2 Scenarios [31]

The approach for the renovation of the Chicago Building, which combines a support–infill system with the use of an adaptable and reusable construction kit, endorses transitions of plot and housing configurations. Figure 10 depicts the adaptability of the dwellings and the plot structure, through the execution of a succession of scenarios (a quarter of a floor plan is shown). An initial housing configuration, providing three housing types for family compositions of one, two and four persons can be easily converted into new configurations answering the changing needs, or dealing with increases and decreases in the number of inhabitants.

## 7 CONCLUSIONS

Just like nature and society, the built environment is an open system, wherein matter, energy and information are exchanged with its surroundings. Thus, a model of the built environment should not be seen only as interactions between the materials, components and construction life cycles; natural, financial and human resources are introduced in one or more cycles and are partially or totally given back to its surroundings. The conservation of these resources cannot be done only by designing artefacts for qualitative use. Complementary to this, designers should bear in mind the temporary character of buildings, their components and the materials they are made of as well as the changing and evolving circumstances which will affect them. In order to promote this, attention must be paid to the design of buildings and the detailing of their components.

Three strategic ways are suggested with the aim of conservation of resources: design for adaptability (construction reuse), design for deconstruction (component reuse) and design for dismantling (material reuse). These three design strategies are not exclusive and can be used in a parallel way. The main benefit of the Hendrickx–Vanwalleghem approach is to (directly) reuse basic elements inside the built environment (or the enveloping material culture) through design of compatible construction systems and kits (design for deconstruction). This way of designing can be combined effectively with the dismantling approach of McDonough and Braungart. Building components can be designed in such a way that technical and biodegradable materials are easily separated, by using basic elements that are made of single materials.

The intention of this paper is not to give an overview of design strategies; rather, it aims to highlight the crucial role the designer has to play in the process of managing a healthy built environment. As an important part of material culture, holistic and trans-disciplinary approaches are required. This implies that besides creative abilities, the designer is assigned to play a moderating role, linking every stakeholder – building users, owners, producers, suppliers, contractors, dismantlers, recyclers and society – with each other.

## REFERENCES


[1] European Environment Agency (EEA). Indicator Fact Sheet Signals 2001 – Chapter Waste, http://themes.eea.europa.eu/Environmental_issues/waste/indicators/.

[2] Eurostat, *Environment & Energy*, http://epp.eurostat.ec.europa.eu.

[3] European Environment Agency (EEA), *Greenhouse Gas Emission Trends and Projections in Europe 2006*, Report No. 9/2006, http://reports.eea.europa.eu, 2006.

[4] Satori, I. & Hestnes, A.G., Energy use in the life cycle of conventional and low-energy buildings: a review article. *Energy and Buildings*, **39**, pp. 249–257, 2007.

[5] Thormark, C., A low energy building in a life cycle – its embodied energy, energy need for operation and recycling potential. *Building and Environment*, **37**, pp. 429–435, 2002.

[6] Brown, V.J., Give me shelter. The global housing crisis. *Environmental Health Perspectives*, **111(2)**, pp. 92–99, 2003.

[7] Henrotay, C., Debacker, W., Mollaert, M., De Wilde, W.P. & Hendrickx, H., 4Dimensional design – a design strategy for efficient shelter and sustainable housing after conflict-based and natural disasters. *Proc. of the 1st Conf. on Ravage of the Planet, Management of Natural Resources, Sustainable Development and Ecological Hazards*, eds C.A. Brebbia, M.E. Conti & E. Tiezzi, Wessex Institute of Technology: Southampton, UK, pp. 341–350, 2006.

[8] United Nations Environment Program, Trends in natural disasters, http://maps.grida.no/go/graphic/trends-in-natural-disasters (accessed October 2007).

[9] Henrotay, C., Debacker, W., Paduart, A., Mollaert, M., De Wilde, W.P. & Hendrickx, H., Sustainable relief and development after natural disasters. *Proc. of the 5th Int. Conf. on Design and Manufacture for Sustainable Development*, Loughborough, UK, Paper 44 on CD, 2007.

[10] Van Mechelen, D., *Beleidsnota 2004–2009, Ruimtelijke ordening – Monumenten en Landschappen*, www.vlaanderen.be/beleidsnotas, 2004.

[11] Debacker, W., Henrotay, C., De Wilde, W.P. & Hendrickx, H., Adaptable vs. lightweight design of transitory dwellings. *Proc. of the 1st Conf. on Ravage of the Planet, Management of Natural Resources, Sustainable Development and Ecological Hazards*, eds C.A. Brebbia, M.E. Conti & E. Tiezzi, Wessex Institute of Technology: Southampton, UK, pp. 331–339, 2006.

[12] Debacker, W., Henrotay, C., Paduart, A., De Wilde, W.P. & Hendrickx, H., Lowering the embodied energy of constructions through reuse of building elements. *Proc. of the 5th Int. Conf. on Design and Manufacture for Sustainable Development*, Loughborough, UK, Paper 32 on CD, 2007.

[13] McDonough, W. & Braungart, M., *Cradle to Cradle: Remaking the Way We Make Things*, North Point Press: New York, USA, 2002.

[14] te Dorsthorst, B.J.H. & Kowalczyk, T., Design for recycling. *Proc. of the CIB Task Group 39 – Deconstruction Meeting on 9th April 2002, Design for Deconstruction and Materials Reuse*, CIB Publication 272, CIB: USA/Germany, pp. 71–81, 2002.

[15] Roston, E., New war on waste. *Time Magazine*, 18 August 2002, www.time.com (accessed October 2007).

[16] Smith, R., Beyond recycling: manufacturers embrace 'C2C' design. *Wall Street Journal*, 3 March 2005, http://online.wsj.com (accessed October 2007).

[17] Hendrickx, H., Solutions derived from natural processes harmonising nature and material culture. *Proc. of the 1st Conf. on Design and Nature 2002. Comparing Design in Nature with Science and Engineering*, eds C.A. Brebbia & L.J. Sucharov, Wessex Institute of Technology, UK, and P. Pascolo, Universita degli di Udini, Italy, pp. 161–171, 2002.

[18] Debacker, W., De Wilde, W.P. & Hendrickx, H., The Hendrickx Vanwalleghem design strategy. *Proc. of Adaptables 2006, TU/e, International Conference on Adaptable Building Structures*, Volume 2, eds F. Scheublin, A. Pronk, A. Borgard & R. Houtman, TU/e, the Netherlands, pp. 6-52–6-57, 2006.

[19] Ching, F., *Architecture – Form, Space, and Order*, 2nd edn, John Wiley & Sons: New York, 1996.

[20] Livio, M., *The Golden Section*, Broadway Books: New York, 2003.

[21] Henrotay, C., Mollaert, M., Debacker, W., Paduart, A., Hendrickx, H. & De Temmerman, N., Structural behaviour of an adaptive construction system for shelter interventions after natural disasters. *Proc. of the 3rd International Conference on Textile Composites and Inflatable Structures*, Barcelona, Spain, pp. 153–156, 2007.

[22] Hendrickx, H. & Ghyssaert, F., Technological construction of an ancient Greek temple. Design of an earthquake proof reconstruction system applied on the Temple of Zeus at Nemea. *Archaia Ellenikê Technologia. Proc. of the 1st Conference on Ancient Greek Technology*, Thessaloniki, pp. 367–379, 1997.

[23] Chini, A.R. & Schultmaan, F. (eds), *Proc. of the CIB Task Group 39 – Design for Deconstruction & Materials Reuse*, CIB report 272, Florida and Karlsruhe, 2002.

[24] Addis, W. & Schouten, J., *Principles of Design for Deconstruction to Facilitate Reuse and Recycling*, CIRIA: London, 2004.

[25] Morgan, C. & Stevenson, F., *Design and Detailing for Deconstruction – SEDA Design Guides for Scotland: No. 1*, SEDA, UK, 2005.

[26] Addis, B., *Building with Reclaimed Components and Materials – A Design Handbook for Reuse and Recycling*, Earthscan: London, 2006.

[27] Brand, S., *How Buildings Learn: What Happens after They're Built*, Penguin: USA, 1995.

[28] Crowther, P., Design for buildability and the deconstruction consequences. *Proc. of the CIB Task Group 39 – Deconstruction Meeting on 9th April 2002, Design for Deconstruction and Materials Reuse*, CIB Publication 272, CIB: USA/Germany, pp. 7–15, 2002.

[29] The World Bank, *World Bank Response to the Tsunami Disaster*, February 2005, http://www-wds.worldbank.org (accessed October 2007).

[30] Henrotay, C., Mollaert, M. & Hendrickx, H., Adaptable construction systems for shelter in emergency situations. *Proc. of the Joint CIB, Tensinet, IASS International Conference on Adaptability in Design and Construction*, Vol. 2, Eindhoven University of Technology, Eindhoven, The Netherlands, pp. 63–67, 2006.

[31] Elsen, S., *Een ontwerpend onderzoek naar de toepassing van aanpasbaar wonen binnen de probleemstelling tot*, Master's Thesis, Vrije Universiteit Brussel, Brussels, Belgium, 2007.