KNOWLEDGE MODEL FOR ASSESSING DISASSEMBLY POTENTIAL OF STRUCTURES

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ABSTRACT

The most important issue regarding a building today is increasing its environmental efficiency, which can be achieved by creating the potential for closed-loop material recycling of building products. One way to achieve this is through the design of demountable structures whose components can be reused in another combination, or recycled. A conceptual-knowledge model for assessing the disassembly capacity of buildings/systems is described in this paper. Disassembly capacity is defined as a single parameter. Since this parameter is a function of a number of factors, such as material levels, structuring, and connections, standard linear latent-variable models are not adequate in this case. Besides the limitation due to linearity, the fuzzy nature of the variables also heavily limits the validity of conventional models.

To deal with the complexity and vagueness of the variables, an intelligent knowledge modeling approach is considered. The model is essentially an artificial neural network with appropriate neurons as information processors, and it is subject to machine learning to establish the model parameters. Each neuron represents a cluster center in the relevant multidimensional space, and the cluster centers are determined in advance, according to the requirement specifications at hand. In this paper, the role of disassembly capacity in sustainable building technology is highlighted. Further an associated knowledge model formulation with underlying intelligent decision-making capability is described. This approach emphasizes the novel application of information technology to building technology.

The aim of the research is to develop a model that will assess the disassembly capacity of buildings and provide support for design for disassembly.

INTRODUCTION

As the problem of environmental degradation increases, designers will come under increasing pressure to provide solutions to reduce energy and material consumption. Design for disassembly is one possible solution, in which the building can be truly deconstructed by a reversal of construction sequences. Disassembly potential is defined as the ability of a building's structure to be selectively taken apart with the intention of reusing and up-cycling some (or all) of its constituent parts. The discussion in this paper is based on the assumption that greater disassembly potential means greater flexibility and environmental efficiency, and therefore, greater sustainability. Two key indicators of deconstruction are independence and exchangeability of building components. Independence is defined as the ability of building parts to be recognized as separate parts of the structure, in terms of functional and material independence. This can be achieved by the separation of functions, systematization of materials into independent clusters, and the design of open hierarchical configurations. Exchangeability is defined as the potential of a component to be dismantled. This can be achieved by the design of simple geometry of component edges, parallel assembly sequences, and use of demountable connection methods. According to the level of independence and exchangeability of building components, all building structures can be grouped into three categories (Figure 1):

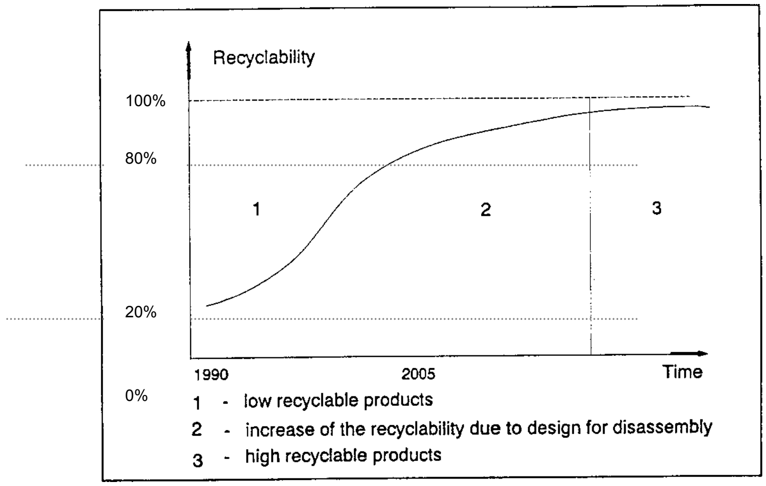

Figure 1: *Three categories of structures [3]*

Category 1

The first category has low disassembly potential where both indicators have less than 30% of their best values. This can be recognized as a standard waste stream in construction. Accordingly, more than 80% of construction waste will be produced during deconstruction. Those are, for example, structures with monolith connections, or structures with complex relational diagrams, where replaceability of one component will influence a number of related components. In this category, building components are being down-cycled, incinerated, and landfilled after deconstruction.

Category 2

The second category has medium disassembly potential, with both indicators having between 30% and 70 % of their best value. Accordingly, between 20% and 80% of construction waste will be produced during deconstruction. These are partially deconstructable structures. For example, about 35% of offices in the Netherlands are constructed out of concrete panels (with integrated facade and load bearing structures) creating a fixed shell. Such fixed shell is filled with flexible installation and partitioning systems. In this category, building components are being recycled after deconstruction.

Category 3

The third category of transformation has high disassembly potential, where both indicators of transformation (independence and exchangeability) have more than 70% of their best values. Accordingly, less than 25% of construction waste will be produced during deconstruction. Such structures are called deconstructable structures. Deconstructable structures define a method of construction in which use is made of integrated structural, mechanical, electrical, envelope, and partitioning systems in a way that will stimulate their independence and exchangeability in different phases of the building's life cycle. The systematization is derived from the fact that different parts of the building have different life cycle and functional expectance, and therefore, should have a status of independent parts within the structure. In this category, building components can be reconfigured or reused after deconstruction.

Sustainable design and construction should aim at promoting Category 3. This paper discusses the development of a knowledge model that can assess the disassembly potential of building structures. Such assessments can be used in two ways:

1. As an indicator of the environmental impact of the building.
2. As decision support for design for disassembly.

FRAMEWORK FOR THE DEVELOPMENT OF THE KNOWLEDGE MODEL

In order to develop the knowledge model, indicators and aspects of deconstruction are defined. A dismantleable building can be defined as a building that is made of pre-made components assembled in a systematic way that is suitable for maintenance and replaceability of single parts. When designing a building that should meet such conditions, the overall relationship between building components should be of primary importance.

This brings us back to the essence of making that is true for any building assembly and material combination and deals with:

1. Natural order within the building that moves from high to low (expressing the load path through a structure);
2. Separate elements, which respond differently to changing conditions (The elements have different life spans, which lead to differential movement, differential durability, or incompatible materials);
3. Interfaces which ensure continuity of functions from one component to another.

These are, at the same time, the three main components of every configuration, namely: hierarchy, material specification, and connections. The two indicators of deconstruction (independence and exchangeability) rely on the specification of these components. Key disassembly aspects that will influence the suitability of a hierarchy for deconstruction are the relational pattern of the structure and the design of the base elements of the structure. Key disassembly aspects that will influence suitability of product specification for deconstruction are: functional decomposition, material levels, and life cycle coordination of material levels. Key disassembly aspects that will influence the suitability of connections for deconstruction are: assembly, geometry of product edge, type of connection, and morphology of connection. Each of these aspects has sub-aspects. In order to define the framework for the assessment model, aspects and sub-aspects are divided into dependent and independent variables.

The Model
The project aims to assess the disassembly capacity of buildings from a knowledge model. The knowledge model is developed by way of information acquired from the building concerned. A simplified basic model is shown below (Figure 2). The model is in a multi-level form with respect to the nodes, which are ranged. In that respect, the relationship between the nodes is in a feed-forward structure, so that causality among various dependencies is maintained. That means that any node in the model can affect only the nodes of higher ranks. The knowledge model has four levels of abstraction.

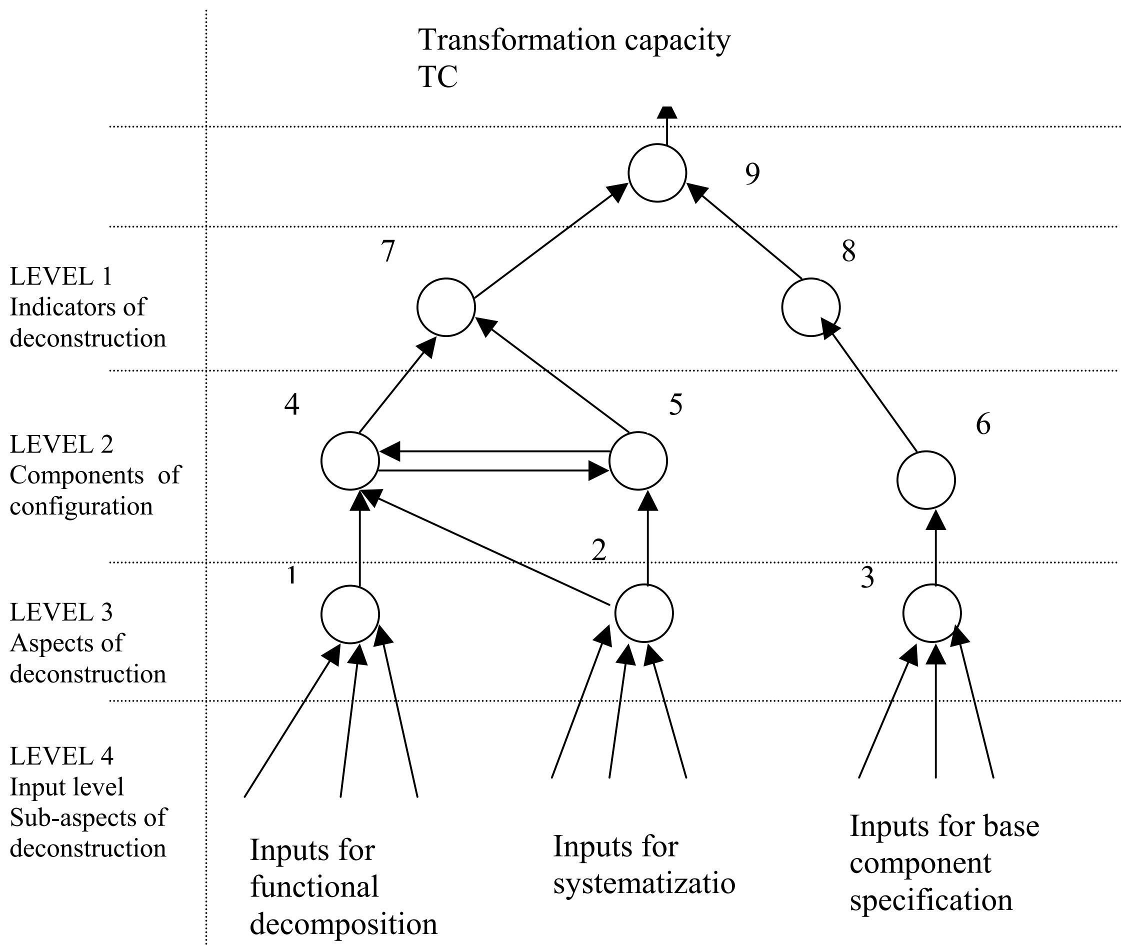

Figure 2: *Simplified knowledge model for the assessment of disassembly potential and transformation capacity TC*

Fourth level
The fourth level is the input level, which consists of sub-aspects (sub-components) and a specification of their impact on the main aspects. This is achieved by the weighting of each relation between a sub-aspect and a main aspect of deconstruction.

The table below represents Fuzzy variables that were used as the input to the knowledge model. Grading is done from zero to one. Zero represents the worst impact, and one represents the best impact on disassembly.

aspects	subaspects		grading
FD FUNCTIONAL DECOMPOSITION	functional separation	separation of functions	1
		integration of functions with same lc* into one element	0.6
		integration of functions with different lc* into one element	0.1
		(fs(n) + n(f)) / n =	….
	functional dependence	modular zoning	1
		Planed interpenetrating for different solutions (overcapacity)	0.8
		Planed interpenetrating for one solution	0.4
		Unplanned interpenetrating	0.2
		total dependence	0.1
		(fdp(n) + n(fdp)) / n =	….
LCC LIFECYCLE CO-ORDINATION	use life cycle/ coordination	long (1) / long (2) or short (1) / short (2)	1
		long (1) / short (2)	0.8
		medium (1) / long (2)	0.5
		short (1) / medium (2)	0.3
		short (1) / long (2)	0.1
		(fdp(n) + n(fdp)) / n =	
	technical life cycle/ coordination	long (1) / long (2) or short (1) / short (2) or long (1) short (2)	1
		medium (1) / long (2)	0.5
		short (1) / medium (2)	0.3
		short (1) / long (2)	0.1
		(fdp(n) + n(fdp)) / n =	
	use lifecycle / size	big (small) element / long L.C.	1
		small element / short L.C. or medium comp./short L.C.	1
		big component / short L.C.	0.4
		big component / long L.C.	1
		material / long L.C.	0.2
		big element / short L.C. or material / short life cycle	0.1
		(fdp(n) + n(fdp)) / n =	
RP RELATIONAL PATTERN	position and type of relations	vertical	1
		horizontal in lower zone	0.6
		horizontal between upper and lower zone	0.4
		horizontal in upper zone	0.1
	base element specification	base element- intermediary between systems /components	1
		base element- on two levels	0.6
		element with two functions (be. and one building function)	0.4
		no base element	0.1

aspects	subaspects		
SYS SYSTEMATISATION	structure and material levels	components	1
		elements / components	0.8
		elements	0.6
		material / element / component	0.4
		material / element	0.2
		material	0.1
	clustering	clustering according to the functionality	1
		clustering according to the material life cycle	0.6
		clustering for fast assembly	0.3
		no clustering	0.1
A ASSEMBLY	assembly direction	parallel	1
		stuck assembly	0.6
		base el.in stuck assembly	0.4
		sequential seq.base el	0.1
	assembly sequences	component (1) / component (2)	1
		component (1) / element (2)	0.8
		element (1) / component (2)	0.6
		element (1) / element (2)	0.5
		material (1) / component (2) or material (1) / component (2)	0.3
		component (1)/material (2) or element (1) / material (2)	0.2
		material (1) / material (2)	0.1
G GEOMETRY	geometry of product edge	open linear	1
		symmetrical overlapping	0.8
		overlapping on one side	0.7
		unsymmetrical overlapping	0.4
		insert on one sides	0.2
		insert on two sides	0.1
	standardisation of product edge	pre-made geometry	1
		half standardised geometry	0.5
		geometry made on the construction site	0.1
C CONNECTIONS	type of connection	accessory external connection or connection system	1
		direct connection with additional fixing devices	0.8
		direct integral connection with inserts (pin)	0.6
		direct integral connection	0.5
		accessory internal connection	0.4
		filled soft chemical connection	0.2
		filled hard chemical connection	0.1
		direct chemical connection	0.1
	accessibility to fixings and intermediary	accessible	1
		accessible with additional oper. which couses no damage	0.8
		accessible with additional oper. which reparable damage	0.6
		accessible with additional operation which couses damage	0.4
		not accessible - total damage of bought elements	0.1
	tolerance	high tolerance	1
		minimum tolerance	0.5
		no tolerance	0.1
	morphology of joint	knot (3D connections)	1
		point	0.8
		linear (1D connections)	0.6
		service (2D connection)	0.1

Third level:
The input on the third level is a specification of the impact that main-aspect components have on three components of the building configuration [performance based specification of product (material levels), hierarchy, and interface]. The weights simultaneously define the hierarchy of importance of each aspect.

Second level:
Input on the second level is a specification of the impact that components of the building configuration have on the indicators of transformation, independence, and exchangeability.

First level:
Input on the first level is a specification of the impact that indicators of transformation have on the disassembly potential, which represents the transformation capacity of a structure.

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 information on the building design properties is concisely represented in the form of a matrix, called the knowledge matrix. In the model, each factor is represented with a node, and the knowledge matrix represents the relation/dependence among the nodes. Thus, nodes represent components, which play a role in the transformation capacity (TC). Each component is described by a fuzzy rule so that the node output is the firing strength of that rule. The inputs to each node are sub-components of the model, which are designed as associated fuzzy variables. Since each sub-component is a fuzzy variable, the imprecision made in its assessment is taken care of. This is accomplished by means of fuzzy logic, which is briefly described below.

Fuzzy Logic
Fuzzy logic explicitly aims to model the imprecise form of human reasoning and decision-making. It is based on the concepts of fuzzy sets [2,3]. A fuzzy set is a generalization of a conventional set, in that the memberships are assigned between zero and one, compared to being purely boolean. The fundamental concept of fuzzy logic is known as a *linguistic variable*. A linguistic variable is a variable that takes values from spoken language. It can be described by:

- qualitatively using an expression involving linguistic terms; and
- quantitatively using a corresponding membership function.

A linguistic term is useful for communicating concepts and knowledge with humans. A membership function is useful for processing numeric input data. Consider x as some variable over some domain of discourse, U, called the universe of discourse. X is a fuzzy set over U. The expression $\mu_X(x)$ is defined as the degree of membership of x in X. The function $\mu_X = f(x)$ is referred to as a membership function, and it represents the degree of association of the variable x with the fuzzy set X. Given a domain of discourse, U, fuzzy sets over U can be identified with a set of names of linguistic variables. Typical fuzzy sets of the speed of a car are shown in Figure 1(a).

Considering the example of driving a car, such a speed variable can be described as *high*, *low*, or *medium*. Although these values do not have precise meaning, a certain distribution between zero and one can be defined and associated with the values. This distribution is represented by a membership function. The membership functions are the fuzzy attributes or semantic labels of the quantity of concern. They are the basic elements of fuzzy computation. Fuzzy logic can be used in various ways. Some examples are the *rule base* in an expert system, *control* in engineering systems, *information modeling* in a knowledge base, and *semantic labeling* in a database. The essential machinery of fuzzy logic is the production of an output (consequent), based on given premises (antecedents), where reasoning plays the major role. This is accomplished by means of statements, which are referred to as *rules*. The general expression for a set of fuzzy rules is:

$$R^i : IF\ x_1\ is\ A_1^i\ and\ x_2\ is\ A_2^i\ ....\ and\ x_n\ is\ A_m^i\ THEN\ y^i\ is\ B^i$$

where R^i (i=1,2,…,l) denotes the i-th fuzzy rule. A basic example is illustrated in Figure 1(b) where two properties related to two items in a construction process are considered. The item may be considered as a building, the associated properties being width and height. The fuzzy attribute values are represented by the associated membership functions. Figure 1(b) shows a fuzzy partition of the height × width space with fuzzy sets. Each division is represented by a similar fuzzy partition scheme, where each triangle represents a fuzzy set. The shaded regions represent the overlapping areas of the fuzzy sets, where each fuzzy variable, i.e. height and width, is represented by two fuzzy sets. The universe of discourse is two-dimensional, and it can be represented by four rules.

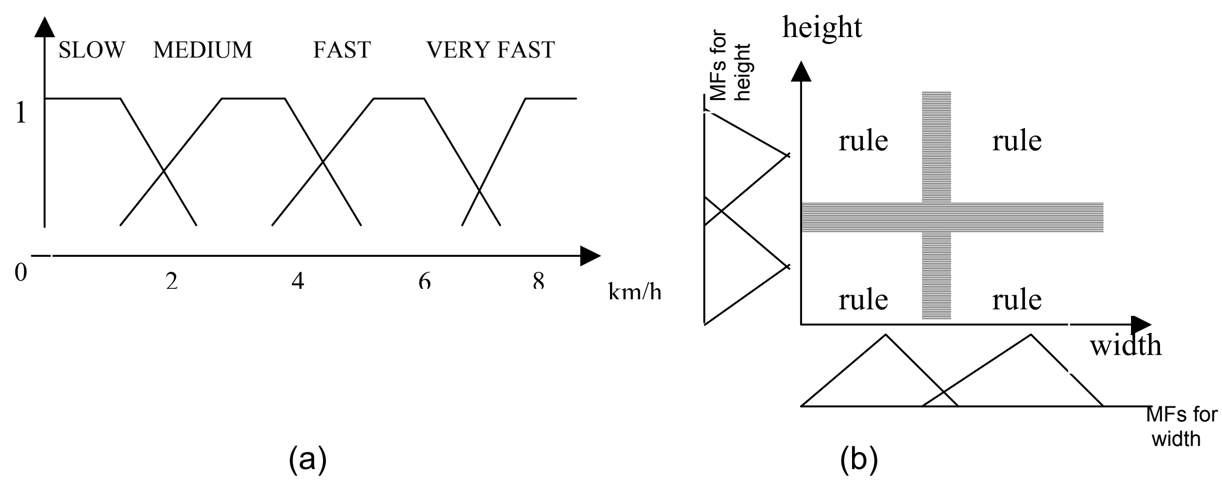

***Figure 3**: Typical fuzzy sets of speed (a) and fuzzy memberhip functions for height and width (b)*

DESCRIPTION OF THE KNOWLEDGE MODEL

In the sample basic model in Figure 2, there are nine main components 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 nine nodes, the transformation capacity is determined. The relationships among main components are represented by relevant weight factors. Each weight is between zero and one, representing the strength of the relation. This is an estimated value with its associated imprecision. Therefore, it is conveniently represented as a fuzzy variable characterized 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 σ are the mean and variance of the Gaussian function, respectively. A fuzzy "AND" is performed by arithmetic multiplication. The mean of each gaussian is characterized by the weight factors of the knowledge model. For $x_p=w_{ij}$, we obtain $\mu(x_p)=1$, so that the knowledge model verifies the transformation capacity 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 can be used for the assessment of TC for the different inputs seen in Figure 2. For these inputs, the membership functions take their respective values and determine the associated TC. Since the knowledge model has a well-defined transformation capacity, TC_s, for the standard inputs, any deviation from these values, i.e., for test inputs, will, to some extent, diminish TC with respect to TC_s.

All inputs and specified weights are calculated by the use of fuzzy logic producing, at the end, an index representing the disassembly potential of the analyzed structure. The test model is optimized for the best value of disassembly potential. Each new case is calculated by a relationship-equation, and is compared with the best values.

CASE STUDY

For the experimental investigation of the model, the Project XX was chosen as a case study. Project XX is an experimental office building designed at the outset for sustainability. The main objective of the project was to develop a building for an expected functional life span of twenty years. After twenty years, all components should be reused or recycled. In the case study, the disassembly potential of the XX building has been calculated for two scenarios:

- Scenario 1: Long term strategy of total disassembly after twenty years.
- Scenario 2: Replace-ability of façade panels in case of placement of an additional entrance and window openings, or replacement of existing entrances.

Disassembly potential of XX building / Scenario 1

The structure of the "Office XX" in Delft is characterized by such systematization where load bearing frame, façade, floor panels, and roof panels were pre-made and independently assembled on the site (Figure 4). The XX building was designed for a short-use life cycle. After twenty years, the building should be deconstructed, and its elements reused in another combination or recycled.

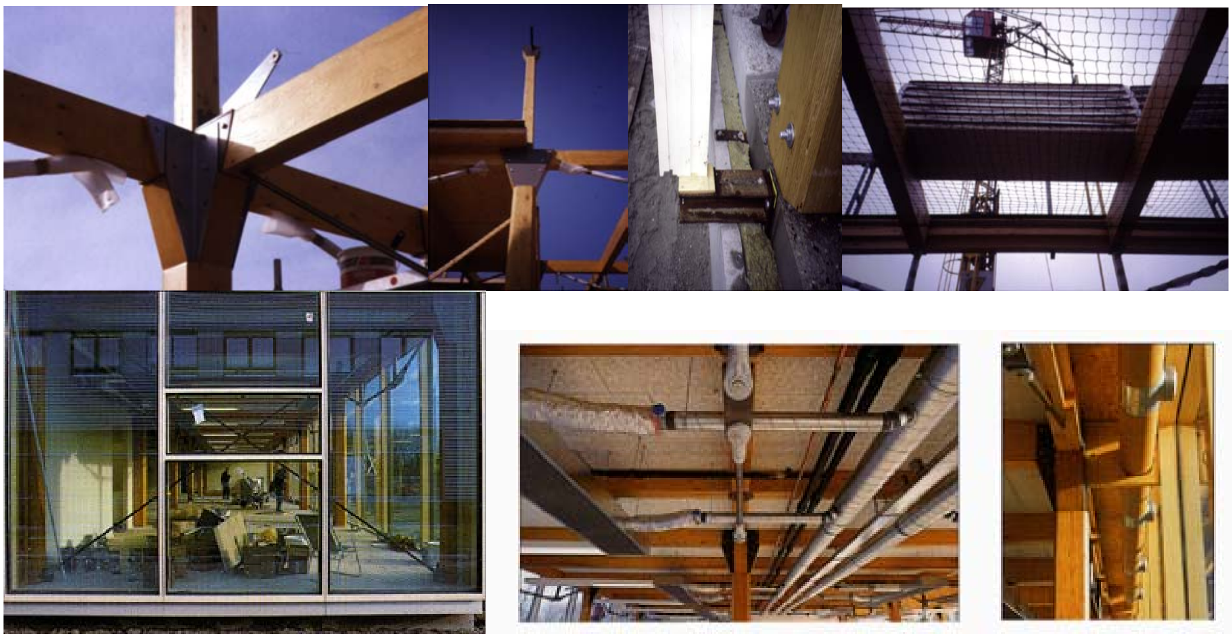

Figure 4: *Assembly sequences of XX Office Building in Delft, The Netherlands [1]*

Structural Frame

Structural frame of the building is made of laminated "Swedlam LVL" timber, with columns of 30x30x350 cm on the ground floor and 20x20x350 cm on the first floor, and beams reinforced with stand-off steel bar lower chords. The frame is stiffened by wind bracing on the ground floor, the first floor, and the roof. The method used to make wooden construction saved 25% of raw material.

Floor on the Ground

Floor on the ground is made of concrete, with 20% recycled aggregate. It is separated from thermal isolation with thin foil so that it could be easily replaced and recycled in the future.

Floor

Floor on the first level is made of wooden sandwich panels (600x500 cm) filled with sand. The panels have an assembly tolerance of 2 cm.

Roof Construction

Roof construction is made of "wood fibre concrete" and recyclable covering. Bitumen is only partly fixed to the layer of thermal isolation.

Building Envelop

Building envelope is made of triple-glass segments. The glass segments are placed in the wooden frame. All connections are kit-lose. Aluminum lintel, which is affixing the glass panels, is affixed with screws to the wooden frame.

Installations

All air ducts are made of carton and attached to the "T" profiles on the ceiling. The canal for the electrical installations and the holes for the water pipes are pre-made in the floor panels.

The diagram above presents the relationships between the main sub-systems in the XX Building and their hierarchical dependencies. The elements of the load-bearing frame are assembled in the first three sequences. They have further relationships with base elements belonging to different subsystems, which were assembled in fourth sequence. The most dependent elements in the XX structure are the load-bearing elements, because of their early assembly and great number of relationships with other parts of the structure. On the other hand, those elements would be the last ones to be disassembled, due to their functionality and long life cycle. Other sub-assemblies of the building have a high level of independence, since they are independent from each other and are only connected to the main structural frame.

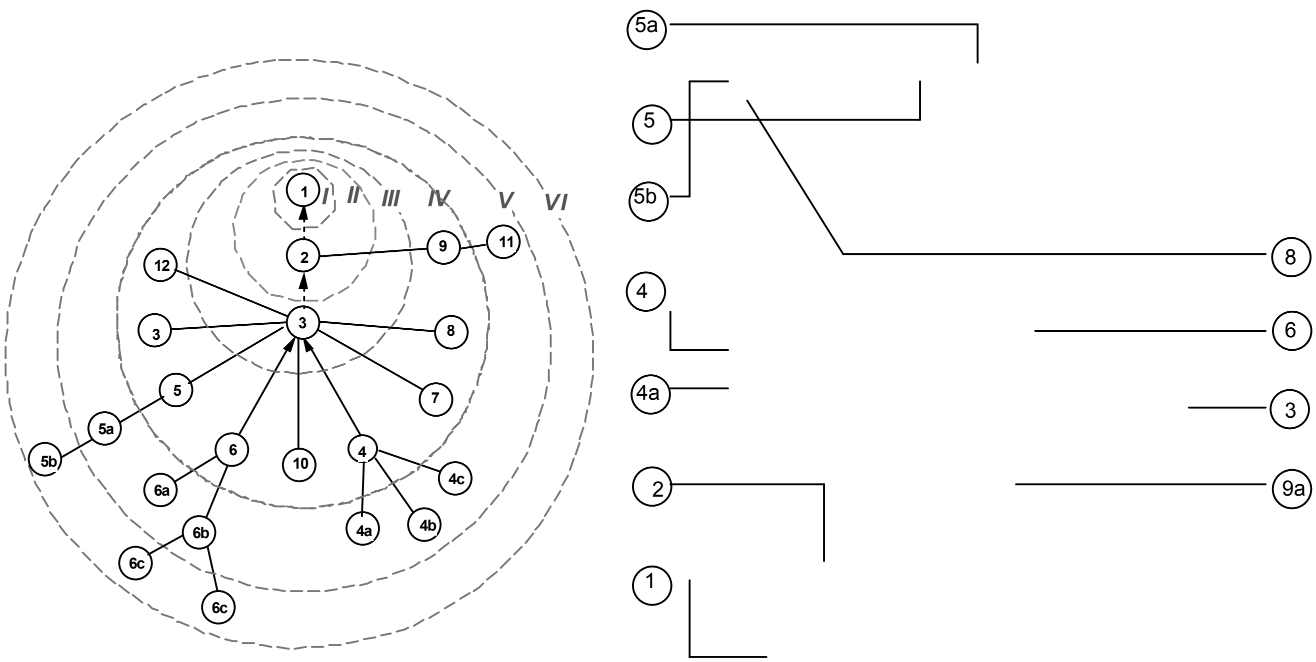

***Figure 5**: relational diagram of components figure 5b total assembly*

The open hierarchical relational diagram and the systematization of elements into independent clusters indicate that two components of configuration, namely hierarchy and material levels, are configured for disassembly. This means, for example, that parallel disassembly sequences of clustered units can be applied, which will save a significant amount of time. Furthermore, separation of functions provides more options for reuse of clusters, and makes it easier to modify them for new use.

However, the design of interfaces, which is also an important element of deconstruction, can be improved for more efficient disassembly. For example, the connection between primary and secondary beams can be characterized as “internal accessory connection,” wherein 30-cm long pins are inserted to connect two beams. Removal of the pins will cause damage to the beams. The material connection is provided between the concrete floor, which makes no room for disassembly. The same is true of the wall finishing.

For that reason, when calculating disassembly potential for the first scenario (total disassembly after twenty years), the suitability of detailing the XX Building for disassembly (which is a function of: type of the connection, geometry of product edge, assembly direction, morphology of connection, and tolerance) is Int = 0.753, or 75%.

The suitability of material systematization (which is a function of functional decomposition and level of systematization) is SYS=0.89, or 89%.

The suitability of hierarchy (which is a function of base element specification, life-cycle coordination, and relational pattern) is H=9.31 or 93%. Accordingly, the total Disassembly Potential (which is a function of independence and exchangeability resulting from the above-calculated parameters) of the XX Building is D =0.912, or 91%.

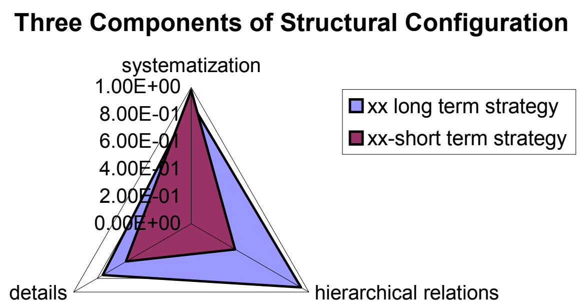

Figure 6: *Disassembly characteristics of components of configuration*

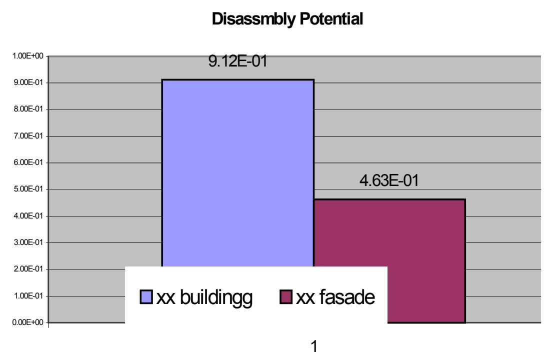

Figure 7: *Disassembly potential of XX structure*

Disassembly potential of XX façade system / Scenario 2

Type of connections

The disassembly potential calculated for Scenario 2, the short-term strategy (suitability of the structure for replaceability of façade panels), is much less than the disassembly potential of the first scenario (Figure 7). Detailing (Figures 6 and 7) is not suitable for exchangeability of façade panels, which accounts for this difference. To obtain more efficient disassembly potential, the following aspects should be improved: assembly direction, geometry of component edge, and type and morphology of connection (Figure 8).

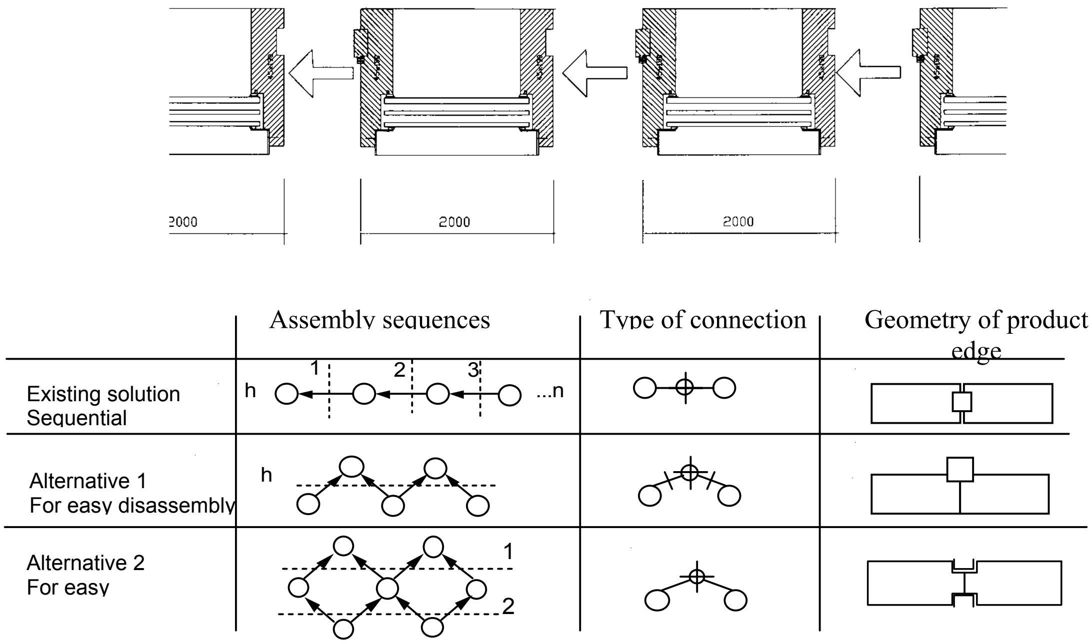

Figure 8: *XX façade system –type of connection and assembly sequences (existing situation on the top and alternatives)*

A linear sequence in assembly of the façade components, in combination with the connection type, results in demolition of at least sixteen façade components in the disassembly of a total structure. However, if one or two façade panels should be replaced, as suggested in the short-term scenario, the façade panels will have to be demolished (no reuse of façade frame can take place).

Hierarchy

Besides the above-mentioned aspects, which determine the type of physical relations within one configuration, other aspects of configuration should also be improved for greater disassembly potential of the second scenario. Hierarchical relational diagrams (Figure 9, right) and disassembly sequences (Figure 9, left) indicate closed and static configuration. This can be recognized through a high level of dependence between the façade and other components, and a lack of base element.

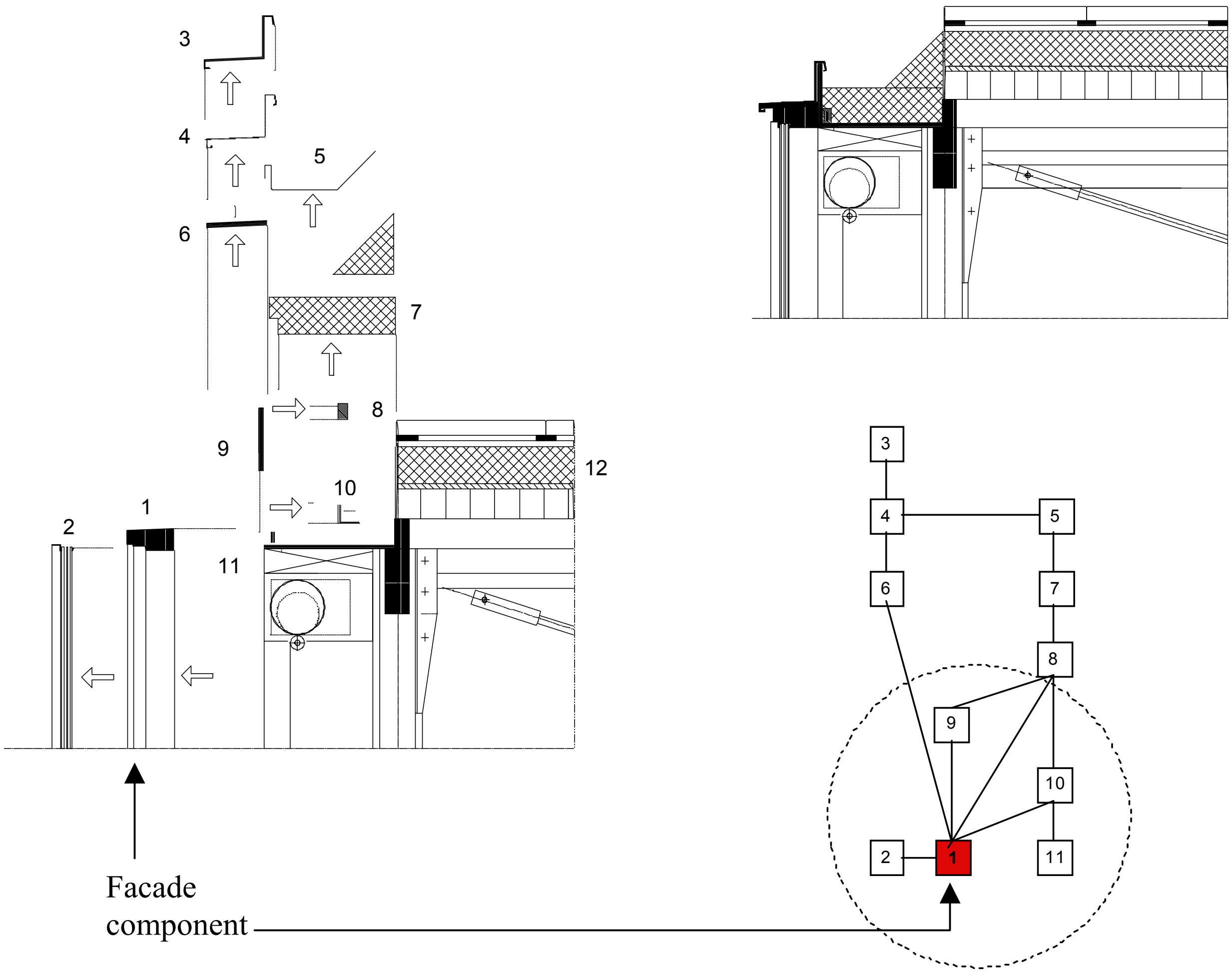

Figure 9: Disassembly sequence 9b Relational diagram

In order to achieve transformable configuration, the relational diagram should be transformed into an open one, with a clearly specified base element (Figure 10). Keeping in mind the above-mentioned disassembly potential of the façade panel, which is calculated as a function of type of connections, hierarchy, and systematization, D= 0.4, which is low. (Figures 6 and 7) This means that the configuration is mainly suitable for recycling, and not for reuse and reconfiguration, if the short-term scenario is applied.

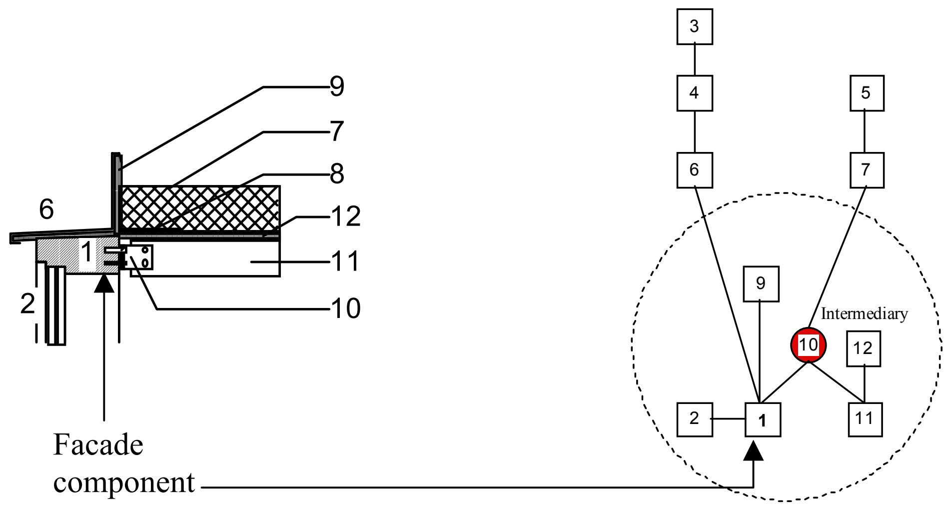

Figure 10: *Alternative solution for better disassembly potential*

CONCLUSION

Disassembly potential indicates the transformation capacity of structures and informs us as to whether specified material systematization, structuring, and detailing (of building or system configuration) are suitable for expected use scenarios. The knowledge model for assessment of the disassembly potential of structures can be used as an indicator of the environmental impact of the building, and as decision support for design for disassembly.

The model is generic in the sense that it can be used to assess the disassembly characteristics of any structure (building, system, or component structure). It gives an indication of the flexibility of a structure's configuration and its potential environmental impact. The model can be used for more accurate life-cycle assessment of structures, since it contains information about assembly methods and morphology of configurations.

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