A NEW APPROACH TO FLEXIBILITY-IN-USE: ADAPTABILITY OF STRUCTURAL ELEMENTS

Roel GIJSBERS1
Jos LICHTENBERG Prof.Dr.
Peter ERKELENS Dr.

Keywords: Adaptability, Flexibility-in-use, Structural elements, Columns, User requirements, Product development, building layers, decoupling

Abstract
The building stock in the Netherlands is seriously out of balance, because the quality of the supplied stock does not satisfy the ever growing demand of users. Flexible use and transformation capacity are a possible solution to create buildings that can adapt to changing user requirements. A building can be divided into a hierarchy of layers: structure, envelope, services and infill. To provide a maximum of possibilities during the lifespan of a building, flexibility needs to be implemented in all layers, by applying building products which are developed for adaptability. However, this is not the case in the existing strategies for flexible design, where, generally, only the infill is considered to be adaptable.

This research project questions flexibility-in-use provided by overcapacity in the structure, because it results in excessive use of resources while the extra capacity may remain unused during the lifespan of the building. Contrary to the building sector, in the industrial product development, it is common practice to apply changes to products and product platforms based on the user requirements. Therefore, in order to improve flexible use of building, we firstly need to research to what extent the user actually desires flexibility. This research project will show the relation between functional requirements and technical qualities and how this relation has been structured. The process of structuring the functional requirements and technical qualities is significant for adaptability performances of building elements. The same also holds for the aforementioned building layers.

To find out whether this approach is satisfactory, a method has been developed to analyze the effect that an adaptable building element has on changing user requirements with regard to its spatial and functional demands. In addition, to research the practicability of this approach, an adaptable column will be developed through a predefined product development trajectory. The combination of both tracks will result in a design methodology for adaptable building elements and a solution for long term flexibility of the building structure. If effective, it may well bring new insights to integrated design strategies for flexibility and transformation.

1 Introduction
The contemporary building stock in the Netherlands is seriously out of balance. This development can be particularly noticed in the office sector, where in 2008 approximately 13% of the total floor areas were unoccupied (DTZ Zadelhoff, 2008); in the housing market, where the quality of the supplied stock does not satisfy the ever growing user demands. Nevertheless, these dwellings remain inhabited because of a quantitative housing storage.

The current difference between the technical lifespan and the functional lifespan of a building is too large. On the one hand, the technical lifespan of a building amounts up to 50-100 years, on the other hand, it may no longer fulfill the function after 20-30 years. It will therefore, be abandoned and eventually be demolished prematurely. The untimely demolition of buildings causes numerous socio-economic and environmental problems such as destruction of capital, waste and energy consumption. Astonishingly, the Dutch building sector contributes approximately 5% to the Gross National Product, however, it produces 35% of the total national waste heap (Lichtenberg, 2005).

Long term strategies are necessary to keep the building stock up to date, even if user demands increase over time. Such a strategy is Slimbouwen, in English: Smart Building. The basic principle of Slimbouwen is to build in a responsible manner with attention to flexibility, comfort, reduction of excessive use of materials and volume, and reduction of environmental impact. Changes in user requirements demand flexibility during the user period. Slimbouwen takes also other concerns into account.

1 Department of Architecture, University of Technology, Eindhoven, The Netherlands, R.Gijsbers@tue.nl
According to Habraken (1961), the building is usually divided in support and infill with regard to flexibility. The infill undergoes changes when flexibility is applied. Daily building practice and the instable market reveal, however, that the applied solutions have not been satisfying until today.

The function of a building consists of satisfying user demands through technical performance. Inevitably, demands remain that will not be fulfilled through mere flexibility of the infill. It is, therefore, of great importance to know the degree of flexibility and adaptability that the individual elements ought to have in order to meet the changing user requirements. The result may be that implementation of flexibility into the infill alone may not be sufficient.

The intention of this research project is to abandon the axiom of the inviolability of the unchangeable support. A method will be developed that predicts whether and where adaptability of building elements has significant value as to the desired functionality of the building. The focus is on the building structure. The belief in general is that material and volume are not applied efficiently in structural designs to attain flexibility. They are normally only equipped with overcapacity to keep possibilities open. Adaptability of the structure combined with limited use of materials is a strategy that has not been explored before. This combination gives more insight into design strategies for flexibility.

The aforementioned methodology will be developed and will be applied to a product development which concerns a moveable column. A process minded approach makes it possible to step away from common premises and to explore under what conditions flexibility is of importance for the user. Widely accepted methods from the industrial product development are used in this project. Contrary to the building sector, in the industrial product development, application of changes to products and product platforms based on user requirements is common practice.

Further on in this paper, more will be explained about user demands, the relation of adaptability and building elements and the actual developments in this research. First, there will follow a short introduction to the Slimbouwen strategy for sustainable and responsible building.

2. Slimbouwen, a sustainable and responsible building strategy

Slimbouwen (Lichtenberg, 2005) is the strategy to make a substantial contribution to an efficient manner of building that is equipped to react better to changing circumstances. Besides, this strategy is accompanied by the aim to build without excessive use of material and with a minimum of overabundant building volume and waste. Slimbouwen introduces a sequential building process (see figure 1), in which steps are physically divided. This results in an industrially organized construction process that consists of the building structure, the envelope, building services and the infill.

![Figure 1 The Slimbouwen sequential building process](image)

In the current strategies concerning flexibility, measures are in general applied from back to forth in the described process, meaning primarily to the infill, secondly to the building services and occasionally to the envelope, however, it is rarely applied to the structure of the building. With regard to flexibility, the structure is normally equipped with extra capacity resulting in large spans and column free floor plans.

From the point of view of Slimbouwen preference is given to build slim (‘Slim building’), e.g. by applying structural beams and flooring elements with small spans. A study that has been executed within this research project illustrates the consequences of large spans and overcapacity of structural elements. See figure 2 for an example of the relation of floor span and weight per m². This example results in a significant increase of building weight that is accompanied by an increase of gross building volume that in its turn causes negative effects on sustainable and economical concerns.

This project examines whether a higher density of columns in the floor plan is acceptable when the possibility is provided to move the columns over a limited distance. It is necessary for this exercise to find out what the boundary conditions are with regard to functional aspects such as: user requirements and building technology concerning technological limitations and possibilities.

I will explain the meaning of both aspects in the following chapters.
3. User requirements

Satisfying user requirements depends on the supplied quality of the building. If user requirements are expected to increase over time, the importance of improvement of the level of functionality in the initial building design is tantamount. The supplied functionality is, therefore, larger and the decrease may be less substantial (see figure 3). User requirements change during the lifespan of a building. People roughly spend 80% of their time inside buildings; logically the user always looks for the solution that meets his/her demands best.

![Improved functional lifespan](image)

Satisfying user requirements depends on the supplied quality of the building. If user requirements are expected to increase over time, the importance of improvement of the level of functionality in the initial building design is tantamount. The supplied functionality is, therefore, larger and the decrease may be less substantial (see figure 3). User requirements change during the lifespan of a building. People roughly spend 80% of their time inside buildings; logically the user always looks for the solution that meets his/her demands best.

In the industry, it is common practice that products are (re)developed to perform according to the wishes and demands of the intended user. Not meeting these demands has as a consequence e.g. disappointing sales results and failure in the competitive market. Strangely enough, the exact opposite occurs in the building industry. The tendency nowadays is, however, users taking initiative to influence the market and they want
their money’s worth. At the moment, the building industry is not organized to provide this need, but the experiences sales figures of the industry should give ample motivation to turn the market from push into pull. The types and terms of change in user requirements in the use of buildings are characterized and illustrated in figure 4 and table 1. They are defined with the help of related research projects executed by Hek et al. (2004), Dobbelsteen (2004) and Post et al. (2006).

![Figure 4 Types of change of user requirements in exemplary floor plan](image)

<table>
<thead>
<tr>
<th>Type of change</th>
<th>Term of change</th>
<th>Aesthetic upgrade</th>
<th>Functional change</th>
<th>Spatial upgrade</th>
<th>Functional upgrade</th>
<th>Technical upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>0y – Trends</td>
<td>everyday</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>1y – Changes in spatial purpose</td>
<td>≥1 yr</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>5y – Spatial adaptation for functional use</td>
<td>≥5 yrs</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>5y – Upgrade interior finishing</td>
<td>≥5 yrs</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>10y – Change of function</td>
<td>≥10 yrs</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>15y – Upgrade of level of comfort</td>
<td>≥15 yrs</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>15y – Functional upgrade</td>
<td>≥15 yrs</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>30y – Technical upgrade</td>
<td>≥30 yrs</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
</tbody>
</table>

3.1 Definition of user values

A significant factor to take into account is to carefully detect user requirements when designing a building that has to contain long lasting functionality. Products in the industrial product development are designed to function properly over time to meet the user’s expectations. The primal functions of the product have to be understood and need to be translated into a solution that satisfies the intended users.

It has proved to be difficult for engineers to point out exactly what requirements are the most important ones for users. Developers have the tendency to approach the problem through the identification of technical shortcomings and apply solutions accordingly. (Griffin et al. 1991).

It seems to be impossible to design an adaptable building for changing user requirements if no research results exist why user requirements change. In fact, the question in building design should be: How can Functional Requirements be translated into Design Parameters. Between these two aspects a line can be drawn. On the one hand we have the domain of the user and on the other hand, we have the product. Consequently, that is the place where functionality needs to be qualified. Both aspects can be placed in a hierarchy where user and product are linked, as seen in figure 5.
The performance of a product is based on its characteristics that depend on the geometric shape of the product and the applied materials. (Eekels, Poelman, 1995). The product fulfills the primary function to a certain extent, which defines the degree of satisfaction of a user requirement. The main reason for the user to use a product is the fulfillment of one or more values, which are the underlying motivations of human behavior. Users may not be aware of this order. For functional analysis however, it is of indispensable importance. A model of the functional performance of a product is seen in figure 6.

The model of figure 6 emphasizes the importance of a profound analysis of user requirements, before the product functions and solution can be determined. The origin of satisfying needs lies in the fulfillments of values that are essential to a specific user. The priority of values differ from user to user, however, the majority of users share the same set of values on the building level. One comment, priorities are slightly different depending on age, gender, family situation and level of income.

To clarify this theory an example: The primary value for the user is well-being and comfort. To satisfy this value, the need for a thermally comfortable indoor climate has to be realized. The function of the radiator is the heating of the indoor space that can be realized by the product property radiation of heat. The shape of the radiator provides a large radiating surface and an internal flow of hot water. The applied material is chosen because of its high radiation coefficient.

3.2 The need for flexibility

Flexibility is viewed as the cure for the rigidity of buildings. It is of great significance to quantify the importance of flexibility measures, such as adaptability for building users. This makes it possible to satisfy user values in an efficient manner. Flexibility is a requirement that generally is in demand based on the functional use, however, users tend to express themselves in terms like: surface area, height of the ceiling, moveable inner walls, spatial relations or number and place of sockets. A survey which was held under 270 occupants of multi-family housing in the city of Eindhoven confirms these findings.

Adaptability relates to the technical performance of parts of the building. In this respect, adaptability is seen as a physical change with the purpose to increase the flexibility-in-use. Manners to adapt building parts are among others: displacement, division of parts, combining parts and upgradeability. Important factors that define the ease of adaptability are: modularity, standardization of components, dry assembly techniques, disassembly, accessibility and technical and functional decoupling.
4. Building layers

As Brand (1994) and subsequently Leupen (2002) observed, a building can be divided into a number of layers. The division is made on the basis of a difference in lifespan and the separation of functional performance. Slimbouwen also divides the building process in layers, four in total that can be seen in figure 1.

The intended lifespan of the individual layers determines the hierarchy of the building layers in the sequential process. In general, an element with a long lifespan has significant more impact on the functional use of building over time than a building element with a shorter lifespan. Elements with a relatively long lifespan are, therefore, placed higher in the hierarchy. The general lifespan of each building layer is shown in figure 7 that is an adaptation of data on the lifespan of building products from Huffmeijer (1998).

![General Lifespan of building layers](image)

The building structure has the longest lifespan and will, therefore, create a framework for the design of the following layers; this also concerns the appliance of measures for flexibility. The bearing structure is important for the usability of spaces that is the most appealing criterion for the user, such as: size, presence of non-removable obstacles and the ability to freely divide the available space. Successive building layers in the process are mutually dependent on each other. A logical dimensional conformity has to be applied to achieve optimal tailoring of spatial and technical parameters. Furthermore, a superior building layer has to leave as much space as possible for the layers next in the hierarchy to allow for optimal performance.

5. Decoupling of building layers

It is recommended that building elements are technically and functionally decoupled to easily apply adaptations. Design for disassembly (Durmisevic, 2006) is a strategy that makes it possible to technically decouple parts of elements or products already in the design phase. The aim of this strategy is to apply changes during their lifetime in an easy manner.

During the design phase, on the one hand distinction has to be made between which functions the individual building parts have to fulfill needs and on the other hand understanding about the building parts that are strongly dependent preferably have a lifespan which is almost similar. Functional and technical decoupling is helpful to optimally utilize the measurements for adaptability during the phase of use. It can be realized if the factor of dependency of Functional Requirements and Design Parameters is taken into account (see figure 5). Technical decoupling is made possible by structuring the relations between Design Parameters and Engineering Metrics.

5.1 Functional Requirements and Design Parameters

Functional Requirements and Design Parameters are preferred to be as independent as possible. Interrelations should, therefore, be minimized. The design has to be technically well-structured to ensure that a specific Design Parameter only fulfills the most related Functional Requirements and has a minimal effect on the other. Table 2 represents a graphical and mathematical model of an uncoupled, a coupled and a decoupled product that has three Functional Requirements and an equal number of Design Parameters.
Table 2 Coupling of Functional Requirements \((FR)_x\) and Design Parameters \((DP)_x\), (from: Mahgrab, 1997)

<table>
<thead>
<tr>
<th>Uncoupled</th>
<th>Coupled</th>
<th>Decoupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>((FR)_1)</td>
<td>((FR)_2)</td>
<td>((FR)_3)</td>
</tr>
<tr>
<td>((DP)_1)</td>
<td>((DP)_2)</td>
<td>((DP)_3)</td>
</tr>
<tr>
<td>((FR)_1)</td>
<td>((FR)_2)</td>
<td>((FR)_3)</td>
</tr>
<tr>
<td>((DP)_1)</td>
<td>((DP)_2)</td>
<td>((DP)_3)</td>
</tr>
<tr>
<td>((FR)_1)</td>
<td>((FR)_2)</td>
<td>((FR)_3)</td>
</tr>
<tr>
<td>((DP)_1)</td>
<td>((DP)_2)</td>
<td>((DP)_3)</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
(FR)_1 &= \begin{bmatrix} A_1 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} A_2 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} A_2 & 0 & 0 \end{bmatrix} \\
(FR)_2 &= \begin{bmatrix} 0 & A_2 & 0 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & A_3 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & A_3 \end{bmatrix} \\
(FR)_3 &= \begin{bmatrix} 0 & 0 & A_3 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & A_3 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & A_3 \end{bmatrix} \\
(DP)_1 &= \begin{bmatrix} A_1 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & 0 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & 0 \end{bmatrix} \\
(DP)_2 &= \begin{bmatrix} A_1 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & 0 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & 0 \end{bmatrix} \\
(DP)_3 &= \begin{bmatrix} A_1 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & 0 \end{bmatrix} \quad \begin{bmatrix} A_1 & A_2 & 0 \end{bmatrix}
\end{align*}
\]

5.2 Design Parameters and Engineering Metrics

Adaptability is primarily a technical quality to achieve decoupling of building parts. According to Slimbouwen, the building process has already been structured in accordance with the assembly order and the difference in lifespan to ease adaptability. Additionally, characteristics like modulation and disassembly are indispensable.

The technical coupling of building layers is graphically modeled in figure 8. The arrows express the coupling of one layer to another. The direction of the arrow indicates the upper layer in figure 8 is linked to the lower layer. In a traditional building layers interrelate in virtually every possible way. The cause is the unstructured and chaotic building process and the use of wet connection techniques. The Slimbouwen building process is intentionally divided into a number of sequential process steps (figure 1). Figure 8 shows how the coupling of layers the theoretically and ideally looks like according to the Slimbouwen process.

Figure 8  Theoretical technical coupling of building layers for traditional building and Slimbouwen

\((Str = Structure, Env = Envelope, Serv = Services, Inf = Infill)\)

In the Slimbouwen process, a building layer that appears later in the process will be coupled exclusively to a layer that has been assembled earlier. In practice however, all layers are coupled to the building structure, which is placed on top of the hierarchy. Some examples are the assembly of façade elements to floors in the façade zone, ducts and piping within floors or an infill wall mounted to the structural floor. All layers that appear in the process are connected to the earlier assembled layers. In figure 9 this insight has been added to the Slimbouwen coupling model from figure 8.
A tool developed by Martin and Ishii (2002) called Design For Variety, makes it possible to quantify the level of coupling of product parts. For this research project, the abovementioned tool, the Coupling Index, was used to provide insight in the differences of coupling between a traditional and a Slimbouwen approach. The level of coupling depends highly on the choice of building products. The point of departure of Slimbouwen is to use innovative products such as flooring with integration of services and flexible infill elements. The traditional manner of building consists mostly of wet connection techniques and a low level of prefabrication. The general outcome is that a Slimbouwen manner of building leads to a level of technical coupling of building layers that is approximately half of the level of coupling of a traditional way of building. Consequently, it will substantially increase the adaptability, on the condition that elements and products are applied that are well-equipped for this purpose.

6. Theoretical Development: analytic method for the desired level of adaptability

The design tool Quality Function Deployment, hereafter QFD, aids to clarify what product features are most appealing to the user and to what extent a product satisfies user requirements. QFD provides insight to the interrelations of user requirements, product features and product functions.

It is necessary to unravel and structure user requirements to fully exploit the opportunities of QFD. The following three steps are required (Griffin, Hauser, 1991): [1] Identify user needs; [2] Structure user needs; [3] set priorities.

In the analytic method to measure the desired level of adaptability, the prioritized user requirements are related to a number of selected forms of adaptability of building elements. This method makes it possible to quantify to what extent adaptability of an element fulfills the required level of flexibility. Furthermore, the consequences of an increase in functional requirements regarding the ability of satisfying user needs can be foreseen. If adaptability measures are sufficient, the level of satisfaction does not decrease when functional requirements increase. This method for adaptability has the ambition to be universally applicable for all building layers and part.

The unique aspect of the developed method is the possibility to implement predictable future changes in functional requirements into the design phase. The purposive approach may lead to less obvious and only minor measures of adaptability in the design, however, with significant positive results for users.

7. Product Development: movable column

This part of the project is specifically aimed at the adaptability of the building structure. In order to realize adaptability, the starting point is a structure that primarily consists of columns, because they optimize the degrees of freedom for flexibility measures. In addition, skeleton steel structures are most likely used because of saving volume and weight.

The analytic method for the desired level of flexibility aids to what extent the adaptability of a column contributes to the desired flexibility of the user.

To restrict the research project, residential functions and office functions are taken into account. Furthermore, the product is intended for large-scale building use, such as: high-rise and semi high-rise building (>4 floors). The solution is initially only intended for flexibility measures in the long run. The types of change that are concerned from figure 4 are: 10y – Change of function; 15y – Functional upgrade; 30y – Technical upgrade. The movable column is not situated in the zone of the façade and does not contribute to the stability of the structure.

The development starts with a functional analysis of the movable column to get a clear picture of the relations of Functional Requirements and Design Parameters. Subsequently, the functional qualities and technical characteristics of the product have to be structured and organized to achieve functional and technical decoupling. Functional Requirements are derived from the outcome of the analytic method and they represent therefore, the true desires of the user. The result will be a set of technological boundary conditions that are significant for the development.
The next step is to generate ideas combined with a morphological analysis (Eekels, Poelman, 1995). Subsequently, the appropriate solutions are weighed. The most optimal solution will be elaborated and tested in a later stage together with the analytic method on a number of often recurring building typologies.

8. Conclusion

The research project is currently in the stage of development of the analytic method. User values and requirements have been collected and categorized. Further, we have started the functional analysis for the movable column. Both the analytic model and the movable column will probably be finished by June 2009.

The combination of both tracks results in a design methodology for adaptable building elements and a solution for long term flexibility of the building structure. If effective, this method will bring new insights to integrated design strategies for flexibility and transformation.

References


Dobbelsteen, A. v.d., 2004, the sustainable office, Delft, Technische Universiteit Delft

DTZ Zadelhoff, 2008, History repeats? De Nederlandse markt voor kantoorruimte, Amsterdam, DTZ Zadelhoff, afdeling research

Durmisevic, E., 2006, Transformable building structures – Design for disassembly as a way to introduce sustainable engineering to building design & Construction, Delft, Technische Universiteit Delft


Griffin, A., Hauser, J.R., 1991, The voice of the customer, WP# 56-91, Sloan WP# 3449-92, Cambridge, Sloan School of management, Massachusetts Institute of Technology

Habraken, N.J., 1961, De dragers en de mensen, het einde van de massawoningbouw, Amsterdam, Scheltema & Holkema

Hek, M., Kamstra, J., Geraedts, R., 2004, Herbestemmingswijzer, Delft, Publikatieburo Bouwkunde, faculteit Bouwkunde, Technische Universiteit Delft, i.o.v. PRC B.V., Bodegraven


Leupen, B., 2002, Kader en generieke ruimte, Rotterdam, uitgeverij 010 Rotterdam

Lichtenberg, J.J.N. 2005, Slimbouwen®, Æneas, uitgeverij van vakinformatie


Martin, M., Ishii, K., 2002, Design for variety; developing standardized and modularized product platform architectures, in: Research in Engineering Design 13, p213-235
