A DESIGN DECISION SUPPORT SYSTEM FOR BUILDING FLEXIBILITY
AND COSTS

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ABSTRACT. Because of possible changes in demand, buildings must have some flexibility. In this paper a building
model, a financial-economic model and a process model will be presented, which together constitute a design decision
support system. This system may be used to decide on flexibility and costs of building variants in all phases of the
design process.

1. Introduction

Quality control is becoming increasingly important in the face of declining quantitative demands
and rising qualitative demands for differentiation in buildings. This shift is occurring just when
the available financial means are shrinking. Investments have to be put to better use. The quality
of a building has to be monitored over a long period of time. And the building must be able to
adapt to changing needs. To decide between new construction and reconstruction, a designer has
to be able to assess the lifetime of a building. The designer will then be able to analyze the effect
of long-term design decisions. A flexible building system is only useful if it is recognized that
buildings have a time dimension.

The objective of this research project is to develop a decision support system which can help
the designer weigh the financial-economic and physical/spatial factors in a decision-making
process. This system can be used as a design tool to facilitate decisions regarding the
programming, design, construction and management of flexible buildings. In particular, we are
concerned with support structures having infill elements with differing lifetimes, based on
dwelling performance and costs. To realize this objective, we have to quantitatively define
flexible buildings for decision-making purposes.

2. Flexibility

Flexibility mainly concerns the time dimension of buildings. In fact, the time dimension (which
does justice to the building dynamics) distinguishes this study from many others in the field of
life-cycle costing. The time dimension involves not only the durability of a building but also the
changes that take place during its lifetime. Buildings have both a duration and a tempo of change.
The building is described independently of the levels of perception. Thus, at least in formal
terms, the situation is identical at every level. This improves the general applicability of our
system. The system is defined in terms of form, function and process; moreover, in accordance
with the research objective, it is also defined in terms of time and cost. We define the subject of
our research as follows: a building - alternatively, parts of a building (building elements), or
groups of parts of a building, where there is a formal, functional, or temporal relationship
between these parts - manifesting itself in reality (empirically), in an abstract representation (a

The concept of flexibility is limited to the ability of buildings to adapt themselves to events (either incidental or intermittent) whose statistical probability can be (more or less) modelled. The (boundary) constraints given in the definition refer to the limitations needed to make the term operational so that measurements and calculations can be carried out. Flexibility can be defined as the characteristic of a building which makes it able, on the basis of its physical composition (its spatial/material characteristics), to adapt or modify itself to changes (its use-oriented/functional and spatial/material characteristics) - which can be characterized as incidental or intermittent events - within technical, legal, temporal, and financial constraints (Brinkman 1989; Prins 1999).

This study is concerned with the flexibility to be achieved by changing the material elements of a building. Thus, multifunctionality as a specific form of flexibility is not discussed here. The diversity in the supply of building types, and the consequent capacity to respond to changing

<table>
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<th>Function: equal</th>
<th>Building volume: not equal</th>
<th>Spatial structure: equal</th>
<th>Material structure: equal</th>
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<td>Function: equal</td>
<td>Building volume: equal</td>
<td>Spatial structure: equal</td>
<td>Material structure: equal</td>
</tr>
</tbody>
</table>

Figure 1. Five flexibility types
demand on the building market, is also omitted from this discussion (Temperley 1991).

Flexibility can be classified into five types, according to the demand for change, by assigning the values 'changes' or 'does not change' to the following parameters: function, building volume, spatial structure and material structure. These five types are the result of operations which can be quantified in terms of material, labour and research tools. These operations form the foundation of our method. We note that this classification is meant to be complete.

We define flexibility types according to the kind of flexibility which is determined by the kind of change (its use-oriented/functional and spatial/material characteristics), as expressed in the following types: re-allocation, extension, re-use, replacement and repair. The content of the five flexibility types distinguished here is summarized in Figure 1. In this figure, each flexibility type is characterized by an icon and a description of the amount of change. The right column identifies which of the given parameters change. The two rectangles in the left column represent a building before and after a change. The surface of the rectangles represents the building volume. The division of the rectangles represents the spatial structure. The lines which form the rectangles represent the material structure. And the filled-in surface of the rectangles represents the function.

Flexibility operations are those leading to the various flexibility types. For the purposes of determining the resulting expenditures, these can be classified as follows: retaining the structure as is, repositioning, upgrading, equivalent replacement, non-equivalent replacement, or various combinations of the above. In Figure 2 the content of these operations is summarized. This figure depicts a building on a time axis on which three moments are distinguished. The filling of the surface represents a service level. A change in form represents replacement; a change in place denotes a non-equivalent replacement.

In our research, the most general statements about change pertain to the flexibility scenario; the most detailed statements refer to flexibility operations. Both of these involve potential events which occur while the building is in use and which initiate the demand for change. Our research covers only those changes that can be predicted and therefore modelled. To define a scenario, we first have to understand what a 'period' is. A period is a time interval between two moments in a scenario and a building's time scale. It is the time span in which the events occurring while a building is in use may be expected to initiate a demand for change. That, in turn, will create a demand for decisions about change to be made in the building.

A flexibility scenario can now be defined as a part of the program of requirements for a building. This part refers to the desired flexibility and predicts future incidental or intermittent events. In this part, the total lifetime of a building is classified into periods on a time scale. Those periods are related to the events initiated by change. The flexibility scenario is part of the planning approach aimed at combining the social, economic and physical plans. The physical component is initially small but gradually gains in content in subsequent stages of the scenarios. During the design phase, the flexibility scenario is developed into the flexibility demand. Both the flexibility scenario and the flexibility demand are placed on a scale, moving from a general program of requirements to concrete performance specifications.

The flexibility supply of a building is the opposite of its flexibility demand. The supply cannot be calculated without first ascertaining the demand. After the demand is known, it can be assessed whether, or to what extent, there is a response to the demand. This response is determined by the intrinsic characteristics of the building: the elements of which it is composed, their lifetimes, and the relationship between the two. The flexibility demand of a building is the articulated need for flexibility. It is expressed as the physical implications which a flexibility scenario has on a specific building. It is also expressed as a series of design alternatives classified according to the analysis of a specific building. These expressions can be translated directly into flexibility operations (Prins and Bax 1992). The flexibility supply of a building consists of the characteristics of a building in physical (material) and legal terms in as much as they answer the flexibility demand.
Buildings and building elements decay in the course of time under the influence of use-oriented and contextual factors. Thus, they no longer meet the original performance specifications. The technical lifetime is the time interval in which a building is expected to meet stated performance specifications. These are based on its intrinsic, initially physical and material characteristics, in which specific maintenance factors are taken into account. The technical lifetime of materials and products can be determined objectively by empirical means. The technical lifetime does not depend on the scenario. The (economic) lifetime is the time interval in which a building is expected to function in an economic sense (maximally equal to the technical lifetime).
measured in periods according to the flexibility scenario. The economic lifetime is determined by
deciding whether the element is still able to perform its function in an economic sense.
It is possible for an element to be replaced before its technical lifetime is over, for reasons
related to its use. In this paper, we consider economic lifetime and use-oriented lifetime to be
synonymous. Whenever we refer to ‘lifetime’ (without using an adjective), we mean economic
lifetime. The economic lifetime does depend on the scenario. The technical and economic
lifetimes determine when it is time to decide whether or not to adapt a building. A decision
moment is any moment marking the beginning or end of a period in which adaptations have to be
made to a building or its elements. An element may have to be replaced when it reaches the end of
its technical or economic lifetime. A building may have to be adapted to a changing demand for
dwelling performance.

3. Building-Oriented Model

In this section, we describe buildings in terms of systems and models. We emphasize their ability
to change, i.e. their flexibility. In even the simplest definition of systems, we apply a hierarchical
classification of sub-systems, which are also denoted as elements. In general systems theory, an
object (and therefore also a building) is seen in terms of the interplay between three partial
systems: a hierarchical system, an aspect-oriented system and a phase-oriented system (Leeuwen
1976). In other words, an element in a building can belong to all three systems at the same time.
Each of the three systems describes, from its unique viewpoint, the building in its entirety.

We define a building-oriented system as the way of viewing a building as a system apart from
its context (system boundary) as consisting of individual elements, each having their own
functionality, which are characterized by their internal and external relationships. Each element is
simultaneously part of three partial systems: a hierarchical system, an aspect-oriented system and
a phase-oriented system. In Figure 3 these dimensions are shown in a three-dimensional space in
which a building can be defined. In line with our research objective, we develop the building-
oriented system into a flexible building-oriented system in three steps. Each step illustrates a
special relationship between the three partial systems.

![Diagram](image)

*Figure 3: Three dimensions in which a building can be defined in (partial) systems*

**Step 1: A special relationship between the aspect-oriented system and the hierarchical system**
In the aspect-oriented system, the building is classified according to a number of objective-
oriented ways of looking at the building. In this research into flexibility, aspect-oriented systems
are determined by the categories of changes that may occur in the building. These potential
changes are reduced to the sources of these changes. Because of the (axiomatic) definition of
flexibility, these sources are defined in terms of their material/technical, spatial/functional, and
social/legal characteristics. Consequently, we can distinguish three types of aspect-oriented systems: technically oriented (aspect-oriented) systems, use-oriented (aspect-oriented) systems and socially oriented (aspect-oriented) systems. Theoretically, the boundaries of the elements on which the three aspect-oriented systems are based will not coincide. This can be seen in the order of magnitude of the elements per aspect-oriented system and consequently in the number of elements needed per system to describe the entire building. Because of the clustering of elements in the various aspect-oriented systems, we can theoretically divide these into the following three cases: (i) interdependence (the number of elements in an aspect-oriented system is not equal to the number in another aspect-oriented system, and elements in aspect-oriented systems cannot be expressed as clusters of elements in other aspect-oriented systems), (ii) unity (the number of elements in an aspect-oriented system is not equal to the number in another aspect-oriented system, but elements in aspect-oriented systems can be expressed as clusters of elements in other aspect-oriented systems), and (iii) similarity (the number of elements in an aspect-oriented system is equal to the number in another aspect-oriented system, and elements in aspect-oriented systems can be expressed as elements in other aspect-oriented systems).

These three cases are shown in Figure 4. The two rectangles represent an aspect-system of a building. The division of the two rectangles represents the division in elements within a specific aspect-system.

![Diagram](image)

**Figure 4.** Three cases for the clustering of elements between aspect-oriented systems

In actual building practice, the typical situation is that of interdependence; unity and similarity only occur when flexibility has been the implicit or explicit objective in the design and building phase. When there is unity or similarity between all aspect-oriented systems, a situation arises in which a socially oriented system consists of a whole number of elements in the use-oriented system, which in turn consists of a whole number of elements in the technically oriented system. In that case, we can state that a socially oriented system arises out of an aggregation of elements in the use-oriented system. And we can also state that the use-oriented system arises out of the aggregation of elements in the technically oriented system.

Although we are dealing with aspect-oriented systems here, this description clearly resembles a level-based arrangement that is characteristic of hierarchical systems. We will make use of this characteristic to express the above-mentioned special relationship between aspect-oriented and hierarchical systems. When there is unity or similarity between the three aspect-oriented systems, the aspect-oriented classifications may correspond to the levels in hierarchical systems. We refer to these levels as aggregation levels. Figure 5 depicts a two-dimensional space in which aspect-oriented systems respectively aggregation levels are set along the axes. A point in this graph represents a system which belongs to an aggregation level as well as to an aspect-system. In the special case of unity or similarity, all these points can be found on the diagonal.

**Step 2: A special relationship between two types of hierarchical systems**

We make use of domain theory to interpret the three-dimensional system-theory model with its three partial systems in terms of decision-making. This means that the three dimensions maintain their own character even though they are interrelated. In this case, the building is also viewed in
terms of the interplay between three types of systems, namely formal, functional and procedural systems (Truud and Bax 1990; Bax 1979). Here, too, a description is given of the building in its entirety at each level. The formal system is arranged hierarchically into levels of magnitude. The functional system involves the performance specifications of the building in terms of use, technique and construction (domains). The procedural system involves the status of the system, which follows from the position in the design and/or decision-making process. The position in that process is determined in part by those persons authorized to make decisions (social/political factors). Figure 6 displays this so-called GOM model. (The name 'GOM' is derived from the Dutch name of the 'Design Methods Group' at Eindhoven University of Technology, by whom this model was developed.)

The formal system consists of generalization or resolution levels, characterized in part by the magnitude of the measurement unit (the module) used to measure the elements at that level. Note that we are still dealing with systems in a static state. Inside the building, we classify the levels according to the fact that an element at a higher level can be developed into one or more alternatives at a lower level in the same hierarchy.

Figure 5. Aspect-oriented systems and aggregation levels

Figure 6. The GOM model

To do this, we must further specify both the spatial and the material components of an element which is, as far as its level is concerned, inherently complex. To put some kind of order into the decision-making process, we must fully understand the concept of a level. This is necessary.
since a decision at a higher level must leave the designer free to make decisions at lower levels. Moreover, decisions at higher levels do not automatically lead to decisions at lower levels. Thus, there are two different ways to hierarchically arrange a building into sub-systems. Although the two are defined differently, there is definitely a correspondence (match) between them. Aggregation levels and generalization levels can be drawn on the two axes of an orthogonal matrix. This matrix is depicted in Figure 7. One point in this matrix represents an element that is part of both a generalization and an aggregation level. In this matrix, elements at any aggregation level can, in principle, be represented at any generalization level. In practice, it is only useful to represent the (composite) elements from higher aggregation levels at more than one generalization level.

Figure 7: Aggregation levels and generalization levels

For single elements from lower aggregation levels, it is only useful to have one generalization level. If the space in the matrix is divided into two parts by a diagonal from the origin, only the elements of one sector are important. Those lying along the diagonal are particularly important. We then seek, given a certain aggregation level, the lowest generalization level for these elements. The characteristics of the elements in the aggregation level, and therefore also the expenditures and costs, can therefore be assigned to the elements in the generalization levels in the form of indices. In this way, we have taken the objective-oriented specification of the original model a step further, leaving the designer some freedom to make decisions.

Step 3: A special relationship between the aspect-oriented system and the hierarchical system

The generalization levels are supposed to be used for structuring and decision-making. In general, these levels go from the general to the detailed, or from a high to a low level of generalization. Decision-making is seen as a formalized process in which the persons who are authorized to do so make decisions about the elements in a building. Those decisions are arranged into levels and domains in successive phases. The systems-theory models described above reveal an intrinsic relationship between phase-oriented systems (arranged in phases) and hierarchical systems (arranged in levels). The level-based hierarchical arrangement can be used to design a decision-making process. The phase-based arrangement of the decision-making process, including the persons authorized to make decisions, can be used to design the building. This relationship between phases and specification levels is illustrated in Figure 8. Flexibility involves change and the sources of change. In the design, building, and management phases, the persons authorized to make decisions are sources of change by virtue of their decisions. Therefore, it is
necessary to define a building system such that a relationship exists between the elements determining the generalization and aggregation levels and those determining the phases occurring during the process. Consequently, we transform the original building-oriented system into a flexibility-oriented system. A building-oriented system is a way of viewing a building as a system apart from its context (system boundary). It consists of individual elements, each having its own functionality. The elements are characterized by their internal and external relationships. Each element is simultaneously part of the three partial systems: a hierarchical system, an aspect-oriented system and a phase-oriented system.

![Figure 2. Phases and levels](image)

The aspect-oriented system can be classified in terms of the technically oriented system, the use-oriented system, and the socially oriented system into three aggregation levels. These correspond to the levels in the hierarchical system: technically oriented level, use-oriented level, and socially oriented level. The hierarchical system can be classified into aggregation levels. These correspond to the generalization and order-of-magnitude levels, according to the following scale: technically oriented level 1:1 - 1:20; use-oriented level 1:10 - 1:100, and socially oriented level 1:100 - 1:500. The hierarchical system can be classified into generalization levels. These correspond to the phases in the phase-based system (which depend on the persons authorized to make decisions).

The term 'system' is used to denote the examination of reality. The term 'model' refers to the pictorial representation of reality. A building which is depicted according to the rules of the building-oriented system is a building-oriented model. Because we examine building-oriented (sub-)systems in terms of flexibility, it is useful to take part of this system and develop it into a new type of system. In this case, we focus on the hierarchical system: the level-based formal part of the building-oriented system, whose elements all change at the same moment of decision. A (building-oriented) flexibility system can now be defined as the level-based system, seen as part of a building-oriented (sub-)system (2), whose elements (sub-systems) all change synchronously. They react to the same source of change, as predicted in a flexibility scenario.

With the aim of making the flexibility systems operational so that design decisions can be made, this system is differentiated into aspect-oriented systems and defined accordingly. We can distinguish various types of systems and therefore various models, depending on the categories into which the sources of change are classified. These systems and models fit into an overall hierarchically arranged system and model. In other words, a particular system or model has to be used as a building block to form a system or model at a higher aggregation level. The technically oriented system is at the lowest level, with the use-oriented and socially oriented levels coming next. The socially oriented level corresponds to the generalization level of the support structures.
with infill elements, the highest level defining the field of study. In analogy to the three types of aspect-oriented systems, we can define three types of flexibility systems. A technically oriented flexibility system is a system, the elements of which change synchronously as a result of their corresponding technical lifetime and their material/technical relationship. In contrast, if the elements change synchronously at the end of a period as a result of their (subjective) spatial/use-oriented relationship and their corresponding use-oriented/economic lifetime we have an use-oriented flexibility system. Finally, the elements of a socially oriented flexibility system, falling under the jurisdiction of the same authorized persons, change synchronously at the end of a period (Ilharco 1985).

To make design decisions about buildings involving flexibility/cost relationships, it is necessary to use a time scale to determine which elements can (synchronously) change at a certain moment. This involves a set of elements in the above-defined systems. However, this set is mainly characterized by its structure rather than its content. Here, too, we are looking at the building in its entirety and distinguishing a set of elements (sub-systems) primarily determined by their lifetime. A lifetime selection set is a set of all elements in a flexibility system which change synchronously at the end of a chosen period. The total costs of a building are determined by the amount and moment at which the expenditures are made. Thus, the way in which a building is arranged into a lifetime selection set is a determining factor. In the flexibility system, the lifetime selection set can be viewed as one of the aggregation levels. Given the definition of the lifetime selection set, these levels have a temporal character. We note that this particular level cannot be linked to the customary decision-making and/or order-of-magnitude level. Moreover, it is impossible to specify any causal source of change which they have in common. Up to now, the systems and models presented here have been abstract. We can model a specific building according to the rules of these systems in reaction to a likewise specific flexibility demand. In that case, these systems and models are made concrete and can be subjected to quantification. Because of the inherent causal hierarchy of change and the synchronism of the change, we refer to the four flexibility models as 'strings of changes' or merely 'strings'.

A flexibility model (string of change; string) can be defined as a specified flexibility system or specified lifetime selection set of a specified building at the technically oriented, use-oriented, or socially oriented level, initiated by the technical lifetime or the flexibility demand at these levels. The string of change is a key concept in this research. In analogy to the flexibility systems, the strings of change can be labelled as follows (Prits and Bax 1991): (i) technically oriented string (this string of change takes the form of a technically oriented flexibility model), (ii) use-oriented string (this string of change takes the form of a use-oriented flexibility model), and (iii) socially oriented string (this string of change takes the form of a socially oriented flexibility model). The three distinguished strings of change are described below.

A technically oriented string is a collection of elements which are changing simultaneously because of the change of one of them. The collection is determined by the material/technical connections between the elements. All elements of the technically oriented string have a technically inseparable mutual connection. This means that if one of the elements is removed, all the others will be damaged. So the technically oriented string is by definition the smallest changing element of a building. To specify a technically oriented string, one first has to detect the so-called 'prime-mover', the element which initiates the change. The technical connections of this prime-mover with other elements defines the size of the technically oriented string. A use-oriented string is a collection of elements which are changing simultaneously because of the change of one of them. The collection is determined by the process of use and the way the building is composed of technically oriented strings. The use-oriented strings can only be specified if a flexibility demand is expressed. Because the technically oriented string is the smallest changing element of a building, the elements of the use-oriented string are technically oriented strings. The relationship between elements of the use-oriented string has primarily a functional character. A socially
oriented string is a collection of elements of which changes are initiated by the decision competence of a certain social group. Besides, the collection of elements is determined by the coherence in life span, use and technical interdependence. All elements of a socially oriented string are subordinated to the same mandate. Because by definition all changing elements in a building are technically oriented or use-oriented strings, these strings form the elements of the socially oriented string. The common distinction of a building in a support structure and in an infill structure is an example of the division of a building in two socially oriented strings. We can now define the terms 'building' and 'flexibility supply'. A building consists of the entire string of change. The flexibility supply is the description of a building in terms of strings of change.

4. The Calculation Model

In this section we add a financial-economic dimension to the building which was modelled in the previous chapter. There, we first described the building abstractly and then more concretely, in physical terms and in terms of time (the duration and tempo of change). The financial-economic dimension is based on the expenditures and costs involved in constructing and maintaining buildings (Prins and Terpelsma 1990). We define expenditures as concrete cash flows needed to construct and maintain a building in a desired state in all design, implementation and management phases. Expenditure is calculated in terms of material, labour and research tools. These can be broken down into: investment expenditures, maintenance expenditures and reconstruction expenditures. Costs can be defined as all conceivable cash flows (derived from the expenditures) in a flexibility scenario. Cost is calculated in terms of strings of change. These include changes due to economics which take place during the anticipated lifetime of the building.

To control expenditures, it is necessary to make decisions based on the costs involved during the entire lifetime of the building and therefore over all the periods on the scenario's time scale. Thus, we have to be able to calculate the costs per period or over several periods (Tempelmann 1982). Effective period costs can be defined as costs which are calculated in terms of a string of change over one or more periods in the flexibility scenario of the flexibility supply of a building. An important research tool is the financial-economic comparison of qualitatively equal design alternatives (i.e. designs with identical performance levels). Over the entire period of development, they constitute the totalised (and subsequently averaged) period costs. These total (average) period costs are determining factors when a choice has to be made from several design alternatives. Total (average) period costs can be defined as period costs totalled and averaged for all relevant strings over all periods in the flexibility scenario of a series. These costs are determining factors when a designer has to select a design alternative for a building. The total (average) period costs are a good basis on which to determine the design. However, they do not indicate the relationship between dwelling performance and costs. Since the period costs do show this relationship, we add the term 'actual' to emphasize this fact.

In fact the costs are determined by a calculation method in the form of a computer program that is both input and output-dependent. The input consists of data about a building, modelled as a flexibility supply consisting of specified strings; the output consists of actual or total (average) period costs. This calculation method can be applied in a variety of ways in design strategies geared to the design problem when there is a specific flexibility demand. In this research we use the term calculation method for an algorithm (computer program) which can calculate several values. Specifically, these are the period costs involved in a given flexibility supply, the flexibility operations derived from this, and the expenditures based on these operations. The calculations are performed for all strings of change where several explicitly stated calculation assumptions are made. In the research project, this calculation method is developed as a user-
5. Process Model and Design Decision Support System

In this section, the modelling process is concluded by combining the flexibility model, the calculation model, and the process model into a decision support model. This process model is a systematic description of the basic activities a designer has to execute when applying the flexibility model and calculation method to the design process. Subject to these activities are the states of the flexibility model and calculation model. The process model is a model for implementation of the flexibility model and the calculation method in a decision support system. The elements of this process model are activities, ordered according to levels obtained from the flexibility model and calculation method. The following activities can be distinguished: generate physical plans, aggregate strings of change, generalize expenditure data, specify lifetime selection set data, and analyze costs. In Figure 9, the process model is summarized.

![Process Model Diagram]

Figure 9. Process model and design decision support system: a systematic description

The first column represents activities which can be characterized as generating physical plans. These activities are distinguished in three levels, characterized by their scale and their information density. Another characteristic is that an element which is subject to the designer's activities on a certain level is manifest as the situation for the design activities on the lower level. In the first column, the building is modelled as a set of generalization levels, of which it is assumed they can be matched with phases in a design process. This level concept of the first column is illustrated...
by an example in Figure 10. At the highest generalization level, a zoning concept is made in which sectors (functional units) can be placed. On the level of the basic variant, these sectors are the situation which can be detailed in design variants. In the example, the sector for the sanitary functions is detailed into a bathroom. On the next level (sub-variant level), this bathroom is detailed into sanitary equipment. On the lowest level (sub-sub-variant level), the technical details are given. For each level, the situation and the elements are specified in the figure. The second column represents activities which can be characterized as aggregating strings of change. These strings have already been discussed in detail in Section 3. The third column represents activities which can be characterized as generating expenditure data in a database. This database can be seen as part of the calculation model. Every time the calculation model is used, new expenditure data can be calculated, generalized and saved. The ordering in levels of the database corresponds with the aggregation levels of the building model.

<table>
<thead>
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<th>INFILL DESIGN</th>
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<td>Detailed sections</td>
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</tr>
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<td>Rooms and spaces</td>
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<tr>
<td>Chairs, tables,</td>
<td>Elements, products and finishes</td>
</tr>
<tr>
<td>accessories</td>
<td></td>
</tr>
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Figure 10: The three generalization levels in the design of an infill system

At the first use of the model, only data on the aggregation level of the technically oriented string can be obtained. Then, only bottom-up processes are possible. After repeated use in several design processes, a database can be created which is also filled with expenditure data of strings of change on the higher levels. This enables the user to execute top-down processes as well. As long as the database is not filled with data on all levels, we prefer to use the term ‘design decision support model’ instead of design decision support system. In the fourth column, the life span properties of the strings of change, defined in the third column, have to be specified according to the flexibility demand. The subject of the activities is the strings of change. By specifying their life span properties, these strings are transformed in lifetime selection sets. The levels in this column correspond with the database levels and the levels of the building model. They are of a temporal character. In the fifth column, the costs of the lifetime selection sets defined in the fourth column are calculated and analyzed. Here the levels are accumulation levels, corresponding with the levels of all previous columns. On the basis of the total average period costs of the highest accumulation level, decisions can be made about two design variants.

Together, the flexibility model, the calculation method, the filled database, and the process model constitute the decision support system, developed in line with our research objective. Thus the term decision support system can now be defined as a system that consists of three components: a flexibility model for modelling the buildings; a calculation method for calculating the period costs of the design alternatives, according to a flexibility demand (including the database); and a process model for the implementation of the flexibility model and the calculation method. This model supports the following four types of processes: (i) decision-making by enabling one to choose among design alternatives in a bottom-up process based on comparison of the calculated period costs, (ii) realization of the optimal design, based on repeated comparison, (iii) calculation of the indices in the form of period costs of the standardized strings of change, in
which the aggregation levels in the flexibility system correspond to specific generalization levels, and (iv) phase-based development of buildings in a top-down process with the help of indices.

6. Flexibility and Costs in the Design Process

Depending on the data available in the database, three design strategies can be distinguished. When the database is not filled, decisions can only be based on (traditional) calculations of expenditure data of technically oriented strings and on the calculations of the total average period costs of these strings of change. Figure 11 illustrates this strategy within the process model (strategy A). After sufficient runs when expenditure data on the other generalization levels are also available, strategies of type B and C (see Figure 11) are also possible. In those cases, costs are calculated on generalized expenditure data of use-oriented strings and socially oriented strings. Then the designer can make decisions about flexibility and costs in the early phases of the design process as well, when only general information about the design variants is available.

Before one can start designing a flexible building with the aid of the developed decision support system, a relevant flexibility scenario has to be formulated. After this is written, one can choose for a bottom-up or a top-down strategy (Tempelmann Plath and Prins 1991). A mix of these two strategies is also possible. We can now define a general strategy for a design process of a building.

![Figure 11. The three strategies within the process model](image)

In this strategy, an attempt is made to optimize building flexibility and to minimize life-cycle costs with the aid of the developed design decision support system. The steps of this general strategy are given below. At the end of the description of each step, the activities in the process model are indicated by the letters A-E (A refers to the activity 'generate', B refers to the activity 'aggregate' etc.):

1) Write a flexibility scenario as part of the brief, in which assumptions are made about all relevant social, political and cultural events which may influence the use of the building. Also write a financial-economic scenario in which the expected developments of the relevant parameters are specified. (A)

2) Design a physical plan which is the basis for the further design of the building. Depending on the design problem, this physical plan can be represented on several generalization levels. (A)

3) Write the flexibility demand for the chosen level. This means that the designed physical plan has to be worked out in a series of plans in time, according to the flexibility scenario. (A)

4) Specify the flexibility operations for each plan in each period in terms of equivalent replacement, non-equivalent replacement etc. (A)

5) Model the physical plan as a set of strings of change corresponding to the relevant generalization level. Which strings of change are specified depends on the technical life span and the chosen connections. (B)

6) Estimate the expenditures if no relevant data is available in the database and generalize these data; otherwise, select the relevant data from the database. (C)
START

Write a flexibility scenario

Design a physical plan on a chosen generalization level

Write the flexibility demand according to the flexibility scenario

Specify the flexibility operations

Model the physical plan as a set of strings of change

Estimate expenditure data and generalize or select relevant expenditure data

Specify life span properties of the strings of change and use them as input for the calculation model

Calculate the costs at all relevant accumulation levels

Evaluate design variant at the highest accumulation level with the aid of the total (average) period costs; analyze the costs at all other levels

Accept variant or design a new variant

STOP

Figure 12: General design strategy, as a ten-step flow chart, when using the design decision support system
6) Specify the life span properties of the strings of change. Use the now available lifetime selection sets, together with the relevant financial economic parameters, as input for the calculation model (CMPC). (D)

7) Calculate the costs with the aid of the CMPC. Generate CMPC output on all relevant levels and decide whether the variant is acceptable or not, depending on the value of the total average period costs on the highest accumulation level. (E)

8) If the variant fits the norm, then decide whether to continue the design process or stop. If the variant does not fit the norm, then analyze how the costs accumulate and try to find clues for lowering the costs in a new variant. (E)

9) Proceed to the next level. Generate a new variant and repeat steps 1 to 9. (E)

10) Select the collection of design variants of strings which together have the lowest total average period costs. (E)

Figure 12 shows this general design strategy as a flow chart. This procedure can be carried out in the design process for new buildings as well as for existing buildings. It is valid for the building as a whole as well as for its constituent elements.

7. Epilogue

We can formulate a few conclusions about the developed model. The most important of these are the following. It is only useful to analyze the flexibility of buildings when the analysis is based on a flexibility scenario. The flexibility scenario should be part of a building’s program of requirements. The flexibility of a building is determined by the number of strings of change it contains, its lifetime, and the technical connections between the strings of change. It is impossible to include price increases in a design or investment decision when the design alternatives contain varying lifetimes. It is preferable to base the calculations on the effective interest and to use a relative (construction) price increase in special cases. Decisions should be made on the basis of the total average period costs. With the decision support system, it is possible to make decisions about the flexibility and costs of the buildings in all phases of the design process, by using feedback and feedforward techniques.

The most important suggestions for further research are summarized below. We recommend greatly expanding the number of case studies and applying the experience gained in the course of the case studies to the system. To be able to generate indices for the various program runs, it will be necessary to elaborate the theory linking the aggregation levels to the generalization levels in the flexibility system. This is also necessary to execute top-down design processes. An important research tool in the field of flexibility would be the development of an intelligent system of drawing and the determination of technically oriented strings based on building elements and their connections. The development of a standard method of describing scenarios and flexibility demands based on these scenarios would significantly accelerate the acceptance of flexibility as an indispensable part of a program of requirements.

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References

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