PRESERVATION OF EXISTING BUILDINGS THROUGH METHODS OF OPERATIONS RESEARCH

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Abstract. The revitalization of existing buildings is getting more and more important. We are facing a situation where in many cases there is no need to design new buildings because an increasing number of existing buildings is not used anymore. The most ecological procedure to revitalize these buildings would be through a continuous usage and by making few or no alterations to the stock. Thus, the modus operandi could be named a "non-destructive" approach. From the architects' point of view, non-destructive redesign of existing buildings is time-consuming and complex. The methodology we developed to aid architects in solving such tasks is based on exchanging or swapping utilization of specific rooms to converge in a design solution. In this regard, it was examined whether solutions for reuse tasks can be produced automatically by the use of optimization processes in floor plan design. These solutions shall be produced by swapping of existing areas. The objective is to obtain feasible planning solutions by means of these computer-based processes, which will serve the architect as a basis for the further editing of the plans. The methodical basis for this procedure is formed by models from Operations Research. The design of the model developed relates to problems in logistics, for example, the loading in trans-shipment centers. It also has analogies to board games like Chess or Go. These games are based on a specific number of fields or crosses of grid lines which are occupied by various tokens. Occupation is subject to a variety of conditions or rules. Compliance to conditions and objectives is clearly defined by the use of these rules. The analogy to our model is the fixed grid, the limited possibility to occupy fields and the fulfillment of an overall goal, i.e., to win the game. Therefore the model does not alter geometric proportions or locations of rooms but changes their occupancy such that a new usage could be applied to the building.

1. Introduction

Operations Research (OR) is a branch of applied mathematics concerning the optimization of processes and methods. Although the methods of Operations Research have been known for many decades, they are rarely used in architecture. There are many reasons for this situation. For instance, researchers have as yet been unable to formalize the traditional design and planning process of the architect in such a way as to derive efficient models for OR. As the work of the architect is increasingly moving from new construction to revitalization tasks, the methodology of the architect in the planning process is changing as well. These changed conditions move OR methods into the focus of planners. They give rise to the assumption that OR is a suitable instrument for the solution of tasks in the preservation of existing buildings.

The research presented here refers to the building stock of the Federal Republic of Germany, which represents about 5,000,000,000 square meters of unused space. However, the developed methodology is independent of location and can be applied to other regions and even building types at any time.

1.1 STATUS QUO OF THE BUILDING STOCK

The qualities of the building stock in the Federal Republic of Germany and the resulting potential for revitalization are closely tied to the developments of history. Marked by the theme of solidity and the ideal of long-term use, buildings from the late 19th and early 20th century were created in a functional way of building that exhibits remarkable economic and ecological qualities. Characteristic for the majority of the building stock from the period of 1871 through 1948 are massive constructions, which lead to inflexible floor plan organizations.

Under the premises of increased efficiency and standardization, the pressure of rebuilding after World War II lead to buildings that were designed for short-term use. Reviving the idea of “Modern Architecture,” the post-war building stock stands out due to flexible system-based constructions and floor plan organizations. However, the stock often exhibits very little economic and ecological qualities.

2. Strategies for Revitalization

Until now there have been no generally applicable strategies for the planning of the revitalization of buildings. There exist attempts at exemplarily describing the revitalization procedure, but these turn out to be procedures tailored to individual cases, which means that they are valid only for a particular project or form of building use and are not fundamentally generalizable. Furthermore, these attempts have specific ideological aspects and are thus marked by a particular point of view that underlies the decision for a revitalization. These ideologies can be of economic, conservational or environmental nature, for example. Generally accepted strategies for the execution of revitalizations do not currently exist. Recommendations and planning templates for new construction and building in existing stock can be found in (BMVBW, 2000), (BMVBW, 2001) and other sources. There are mainly two different strategies that can be determined as potential procedures for revitalization measures: Conversion and change of use.

2.1 CONVERSION

A building undergoes structural changes in order to adapt it to such requirements as would be made of a comparable new building. This procedure is the most common kind of revitalization. The structural changes of the object are problematic in terms of ecological planning guidelines because there are usually massive alterations of the building's substance.

2.2 CHANGE OF USE

A building is changed in terms of its use profile. Very little or no structural changes are executed. The principle behind this procedure is the swapping of areas or entire buildings. Change of use makes ecological sense but can usually not be realized completely because the old and new use profiles would ideally have to be identical. Since change of use provides the greatest potential for ecologically sensible revitalization, we will focus on this strategy exclusively from here on.

2.2.1 Methodology

Change of use is related to an instrument that was originally used for reallocation of land in forestry and farming (Bundesministerium für Verbraucherschutz, 1953). It is rarely used in architecture because its potential had not been understood until now. In principle, this model prescribes swapping of areas between several parties if the owner's requirements cannot be met by his land and if the purchase of another piece of land would enable these requirements to be satisfied. Obviously, the requirements the parties have of each area to be swapped must be different in order to perform a swapping that makes sense. In architecture the swapping of areas (change of use) means therefore to balance the weaknesses of an existing building by changing the user or use profile (Kahlert, 1999). Examples for such weaknesses are the low flexibility of massively constructed administrative buildings from the early 20th century or the poor climatic conditions of administrative buildings from the 1960s and 1970s, which can be compensated without structural alterations only if these weaknesses are of little or no relevance to the new user profile. The primary advantage of area swapping is that its execution is independent of the way a building is constructed. When an existing building is decomposed into structural units in the conversion process, the question arises whether primary, secondary, and tertiary structures can be separated from each other. With area swapping, however, only the organizational properties of the spaces to be swapped and their connection to transport paths and auxiliary spaces are relevant. Area swapping is based on organizational decomposition of a building into individual areas that can be used independently of each other and, at the same time, offer access to – potentially shared – auxiliary areas. Therefore, area swapping is suitable for all building types with sufficiently large utilizable space and appropriate organizational divisions. Both organizationally connected room units and floors as well as individual rooms can be swapped. Area swapping can even be applied to room units located on different floors. This can be extended to the swapping of entire buildings or groups of buildings. Both models of swapping are especially suited for institutions or companies with an extensive building stock. In addition to the positive ecological impact on the building stock, the swapping of areas and buildings is therefore also an economic instrument for the administration and use optimization of real estate in Facility Management. Although area swapping is independent of the way a building is constructed, it is particularly suited for building stock with massive constructions and inflexible floor plan organizations since this type of buildings almost exclusively exhibits load bearing structures that complicate structural alterations.

2.2.2 Procedure

The essential criterion for deciding to revitalize such a building is whether the room program proposed by the architect can be satisfied within the existing structure of the building. This complex task quickly leads to planning solutions that change the existing building through massive structural modifications towards satisfaction of the room program. However, given the premise of sustainable treatment of existing buildings, decisions for the continued use of a building should be reached by taking into account the greatest possible conservation of present structures and the least possible alterations of their architectural state.

This course of action, which has found little consideration in previous revitalization efforts, can therefore be called a “non-destructive method.” Further, this research paper proposes the hypothesis that the comparison of the room program with the floor plans of a building essentially is a combinatorial problem. Under this assumption it is examined whether solutions for conversion and reuse tasks can be produced automatically by the use of optimization processes in floor plan design. These solutions shall be produced by reordering or swapping of existing areas. The objective is to obtain feasible planning solutions by means of these computer-based processes, which will serve the architect as a basis for the further editing of the plans.

3. Model Formation

Non-Destructive Models derive from the non-destructive reuse strategy, that is, the attempt to reuse the existent room structure of a building while mostly refraining from the removal of walls and other structural elements. The main criterion for this model are the existing structures between room units, for which it is determined whether they agree with the structures of a planned future use. The areas used by the Non-Destructive Model are assembled from existent rooms. It is possible, albeit not desirable, to apply the model to even smaller units, for example, areas decomposed by a grid. This model aims at finding areas in the existent floor plans that satisfy the requirements of the room plan. This is achieved by comparing the properties of the existing areas with the properties of the areas in the room plan. No structural alterations are performed on the existing building. This is possible because the Non-Destructive Model does not change the geometric shape of a room but merely its use profile.

The methodology of the Non-Destructive Model is similar to the structure of board games such as Chess, Go, or Connect Four. These games are based on a number of fields or points on a grid, which are occupied by pieces according to certain conditions (game rules). The objective is clearly defined, as it is for the Non-Destructive Model. Both share similar features such as a fixed grid, a restricted possibility to occupy fields, and the satisfaction of a higher objective, that is, to win the game.

The Non-Destructive Model focuses on the geometric shapes of existing room limits or the orientation of system lines, such as those of the static system or the grid units of structural components. This abstraction of floor plans ensures non-invasive treatment of existing buildings. Units of the Non-Destructive Model are not limited in their geometric shape. As nodes of a graph they can represent any shape, including non-rectangular shapes.

3.1 SEQUENCE OF EVENTS

The architect begins by decomposing the building's floor plan into units corresponding to the existing rooms. In view of the later stage of satisfaction of the goal definition, this procedure permits change of use without structural modification. An important factor for successfully finding a solution is the definition of relationships between these units. The most significant relationship is adjacency, which ensures that units in a newly formed group are also adjacent. Adjacency is defined as a unit having at least one other unit as its neighbor. In other words, there must be an edge where two areas of a unit touch each other. Since a complete integration of a room program into an existing building is rarely possible, the room program may optionally be decomposed into logical units. Equivalents of such units can be searched for within the floor plan. However, chances of finding a perfect fit to the stock are still low for such a decomposition. For this reason, matches between units can be defined as partial goals. Maximizing a weighted sum of these partial goals can then be defined as a superior objective. Although this procedure has a negative effect on the quality of potential solutions, it does increase the size of the solution space. The solution can be further influenced by applying conditions to the units of the room program. A unit may be defined, for example, by individual unit size, the total size of units, and the number of areas per unit. By combining these definitions, the variance within a given floor plan constellation can be increased.

3.2 MODEL COMPONENTS

This model does not have the Destructive Model's restriction to rectangular unit shapes. The advantage of the Non-Destructive Model is that it can be applied to any floor plan constellation. This model is especially suited to the planning needed for complex existing stock without ordering structures. The purpose of this model is to enable the swapping of units without structural alterations. Swapping in this context shall mean the exchanging of the names (and uses, respectively) of a unit i with a unit j. This swapping is performed by assigning a unit to a group from the room program and is displayed by the change of its name $(label)$. The units remain geometrically unaltered, unit i becomes unit j and vice versa. However, this exchange is not just performed between two units but also between all units of an entire floor plan. The details from the room program are used as input parameters. Among these are details on groups, that is, connected and adjacent units, as well as their size and number. The Non-Destructive Model works without any geometrically based auxiliary conditions between parameters of individual units. It defines merely the adjacency between existing units.

3.2.1 Constants

The model does not contain constant parameters that are used in the optimization process. The nature of this model is to keep the unit positions constant. However, the potential solution space may be enlarged by varying the units in their size and adjacency by changing the graph.

3.2.2 Variables

The most important variable in the optimization process of this model is formed by an adjacency matrix. This matrix describes the adjacency between units of the existent floor plan. The manner in which this relation is defined may be modified and can be defined by the architect according to the specific project requirements. Adjacency is not required to be understood as immediate adjacency to another unit. Units that are opposite each other but touch a mutual transport space may be considered neighbors. Each unit is represented by a node in the graph. The graph's nodes are searched for all groups from the room program that are formed by several units. If no solution is found, auxiliary conditions represented by the following variables can be modified. This modification correlates with an adjustment of the room program. In terms of sustainability, this is the preferred procedure:

nbreOfGroups	number of groups of connected units in room program to be found
sizeGroups	size of groups of connected units in room program, in square meters
groups	number of units within a group

Another, but less ecological, option for finding a solution is to modify the adjacency matrix. The matrix is enlarged by additional structural or organizational decomposition of the floor plan into smaller units, creating new room constellations. This procedure requires adjusting the following variables:

A	adjacency of existent units in floor plan
nbreOfNodes	number of existent units in floor plan
sizeNodes	size of existent areas in floor plan, in square meters

An extension of the adjacency matrix does not inevitably result in a structural modification of the floor plan. Even so, this very ecological procedure may require larger distances between neighboring nodes. If the number and therefore the size of units is altered, however, structural changes of the building are a practical consequence. In many cases, this is not as much of a problem in ecological terms as classic conversion since interventions are manageable if the matrix is incrementally modified. Removal or addition of walls alter the adjacency of units and lead to potentially greater flexibility for the process of swapping units.

The optimization process results in new values being assigned to the variables. These values correspond to membership in a group whose name (depending on the number of groups) is assigned to the variable (*label*) :

label names of groups formed from room program

3.2.3 Constraints

The model is based on adjacency relations between existent units and adjacency relations between the found groups. Adjacency is defined as a unit having at least one other unit as its neighbor. Furthermore, a feasible solution must meet the following auxiliary conditions:

The number of units in a group matches the defined number of units for this group.

The sum of the size of all units in a group (in square meters) is larger than or equal to the defined group size.

The units in a group must be adjacent.

3.2.4 Upper and Lower Bounds

The Non-Destructive model utilizes upper and lower bounds when determining the deviation from the total group size required by the room program. These bounds are used to extend the potential solution space.

pso upper bound, i.e., percentage of required group size that must at most be met (usually ≥ 100%)

psu lower bound, i.e., percentage of required group size that must at least be met (usually ≤ 100%)

3.2.5 Objective Functions

In this model, objective functions are in theory obsolete since the satisfaction of auxiliary conditions includes the satisfaction of the goal, i.e., finding the defined groups, group sizes, and numbers of units within groups (Constraint Satisfaction). It is, however, possible to define superior goals. Such superior goals weight the search for a solution. If, for example, all conditions except one are met within a floor plan (e.g., one group is five square meters too small or large), it would not make practical sense to not actually swap the units regardless. For this reason, such solutions that are made possible by upper and lower bounds are considered by the performance model in the shape of weighted goals.

3.2.6 Search Strategies

The Non-Destructive Model does not utilize search strategies for the purpose of constraining the solution space of the optimization problem. It merely uses a broad search (Jungnickel, 2005) in order to ensure graph connectivity.

3.3 MATHEMATICAL MODEL

The Non-Destructive Model focuses on the geometric shapes of existing room limits or the orientation of system lines, such as those of the static system or the grid units of structural components. This abstraction of floor plans ensures non-invasive treatment of existing buildings. Units of the Non-Destructive Model are not limited in their geometric shape. As nodes of a graph they can represent any shape, including non-rectangular shapes.

3.3.1 Conventions:

$G=(V,E)$	graph with
V	set of nodes
$E \subseteq V \times V$	set of edges
$nbreOfNodes$	number of nodes $(=\vert V\vert)$
$Node_i$	node i of graph $\left(i \in \{1,...,\vert V\vert\}\right)$
$nbreOfGroups$	number of connected groups (sub graphs) to be found
$Group_j$	group j
$label_{ij}$	means that $label_i = j$

3.3.2 Variables:

$A=a_{ij}$	adjacency matrix of G with $a_{ij}=\begin{cases}1, \text{ if } (i,j)\in E \\ 0, else\end{cases}$;
$sizeNodes_i$	size of node i in square meters
$groups_j$	number of required units in group j
$sizeGroups_j$	found total size of group j in square meters
$sizeRooms_{jk}$	size of room k in group j $\left(k \in \{1,...,groups_j\}\right)$
psu	lower limit: percentage of required group size that must at least be met (usually $\leq$ 100%)
pso	upper limit: percentage of required group size that must at most be met (usually $\geq$ 100%)
$label_i$	group to which node i belongs

Number:

$$\sum_{i=i}^{|V|} label_{ij} = groups_j \quad \forall j \in \{1,...,nbreOfGroups\}$$

Size:

$$\frac{pso}{100} * sizeGroups_j \geq \sum_{i=i}^{|V|} label_{ij} * sizeNodes_i \geq \frac{psu}{100} * sizeGroups_j$$
$$\forall j \in \{1,\ldots,nbreOfGroups\}$$

4. Examples

Let there be given a floor plan with 24 rooms and a total area of 369 square meters. Within this floor plan, find 4 room groups (RG) that contain 7, 6, 6, and 5 adjacent rooms (R) whose respective room group area in square meters equals the room group areas (RG1, ..., RG4; $\sum$ = 369 square meters) required by the room program. Use a Lower Bound if no perfect solution exists. A preliminary calculation of this example confirms that there is no solution satisfying all auxiliary conditions. The application of a lower bound of 89% produces 6 solutions within 94 seconds. This lower bound defines the largest deviation of an individual unit from the target function (room group size). The total size of the groups, i.e., their distribution on the entire floor plan, is always satisfied by the use of lower bounds. However, since an exact allocation of the existing rooms to the given group sizes is not possible in this example, the prototype tries to determine the constellation having the smallest deviation. For this purpose, some groups are initialized with larger values than those required, others groups with smaller values. This results in an approximation of the values defined by the user.

More complex calculations consisted of 78 rooms within which we were searching a room-program with 17 rooms. Each room had to fulfill specific requirements regarding its floor space and adjacency to other rooms. Our model found 4935 solutions to the problem. All solutions ranged within a 3% tolerance of the specified objectives. To further judge upon these solutions we integrated additional quality-ratings and performance measures as well as penalizations in the model. These aid the architect in finding the most appropriate solution that might as well meet further demands.

5. Conclusion

With the aid of the Non-Destructive Model developed and the language used (Van Hentenryck and Lustig, 1999), it is possible to represent two- and three-dimensional spatial structures. A two-dimensional matrix can be applied to one or several stories, which can even be located in several buildings. Entire buildings or real estates, including stories, can be represented by block matrices. Using the developed prototype, extremely complex architectural reuse problems have been solved. Here, “extremely complex” refers to problems that could not be solved by an architect in a reasonable amount of time. Furthermore, the prototype can be used to generate all perfect solutions to an optimization problem, which beyond doubt can not be worked out by an architect. If the target functions can not be completely satisfied, the prototype provides weighted target functions which permit the generation of approximate solutions. The number of generatable solutions depends on the granularity of the network topology. The finer the network, i.e., the higher the number of edges connecting the nodes, the higher the probability of reaching a perfect solution. The performance of the generatable solutions is therefore highly dependent on the architect's readiness to refine the network. Although this refining of the network may increase the distance between room units in a generated solution, it is still recommendable in light of the premise of resource-preserving treatment of building stock. The performance of generated solutions is automatically measured.

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