A DECISION SUPPORT SYSTEM FOR HOUSING OF (PUBLIC) ORGANIZATIONS

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ABSTRACT. In this paper we present a hierarchical decision support system for the allocation of organisations to available buildings, and for the allocation of employees of an organisation to the work units of a building. For both allocation problems a mathematical model and optimisation algorithm is developed, taking into account the relevant criteria, such as the extent to which the allocated floorspace is in accordance with the standards, and the extent to which departments are housed in connecting zones of a building. The decision support system is illustrated by two practical applications.

1. Introduction

The Dutch Government Buildings Agency (GBA) is responsible for the provision of work space to 170,000 people in the service of the Dutch central government. The building stock consists of about 4,500 buildings with a gross floor area of 6.5 million square metres and an estimated replacement value of about 10 billion U.S. dollars. With the exception of computer and furniture facilities etc., the housing cost of a work unit is more than 6,000 U.S. dollars per year. Thus, the housing cost of the employees of the Dutch central government adds up to more than 1 billion U.S. dollars per year.

The main objective of the GBA is to provide adequate housing for the government organizations in a flexible, effective and efficient manner. In the realization of its main objective the GBA has to take into account many developments, requirements and objectives, including the following. During the eighties several retrenchment operations were put into effect by the Dutch government, and many others are still expected. A crucial aspect of these operations is the wish to realize a smaller (but more effective) government apparatus. However, the extent of the cut-back in number of government employees is only partly known. Nor is it known precisely when these reductions will be realized, but they are obviously of enormous importance for the GBA. As a result of such an economizing measure, the GBA was furthermore given the task to reduce the yearly housing costs by 10%. There is a growing number of part-timers and a growing rate of churn in the organizations, which have considerable repercussions on housing requirements. Housing is increasingly understood as a means of production. That is, analogous to human capital and material resources (such as computers), the quality and size of the housing stock and its allocation to organizations and employees has to be determined in such a way that the size and the quality of the output of the organizations is maximized. To assist the GBA in realizing its

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objectives we developed a method to analyze, evaluate and optimize the matching of the available accommodation of real estate with the housing requirements and needs of the government organizations, taking into account the housing standards and policies of the central government.

In the process of evaluating and improving such a matching, many criteria have to be taken into account. A first criterion is the degree to which the standards set by the central government deviate from the numbers of square metres which are actually assigned. These deviations not only have to be minimized on a national, regional and urban level, but also the space assigned to the individual organizations and employees has to be in accordance with the norms. The relevance of this criterion is evident: if too much space is assigned, the housing cost will be too high, and insufficient space will affect the production of the organizations. A second criterion is the extent to which each organization is concentrated in one building. This criterion is of obvious importance: if an organization is scattered over more than one building, this will clearly hamper its readiness and production. Other criteria concern the distances of the buildings to a station of public transport (central government policy), the extent to which departments of an organization are housed in connecting zones of a building, etc.

It is practically impossible to take all the relevant criteria into account simultaneously. For example, is a matching in which an organization is concentrated in one building with a 14% shortage of space, preferred to another matching in which the shortage is remedied at the expense of a scattering over two buildings? If not, is the new matching nevertheless preferable if it implies that the situation of other organizations can be significantly improved? In order to be able to take all these aspects into account, a multi-criteria approach has been developed. In this approach each criterion is assigned a weight which reflects the relative importance of the criterion. Next, a score is assigned to a matching with respect to each relevant criterion. These criteria scores are aggregated to a total score of a matching using the criteria weights. For example, assume that only the used space and the concentration of organizations would be relevant, with relative weights of 40% and 60%, where the criterion scores of a matching would be respectively 80% and 100% (i.e. each organization would be housed in one building). Then the total-score of the matching would be $0.4*80\% + 0.6*100\% = 92\%$.

This multi-criteria approach not only enables the GBA to evaluate and analyze a current matching, but it also provides the basis for a systematic comparison of the pros and cons of adaptations and movements. That is, a matching can be optimized by moving (parts of) organizations or departments form one building (or zone of a building) to another in such a way that the total score of the resulting matching is maximized, taking into account certain conditions which matchings have to satisfy and the cost of moving. To carry out these optimizations, algorithms have been developed which are based on methods from Operations Research and Management Science.

The multi-criteria approach and the optimization algorithms have been implemented in a decision-support system called BOAST: Buildings Optimization and Analysis SysTem. BOAST is an interactive decision-support system, not a decisive system, which is intended to assist the analysts of the GBA rather than to replace them. In such an interactive decision-support system, the analyst and the computer join forces to obtain solutions which neither of them would have been able to obtain separately. The computer is unbeatable in quickly evaluating matchings, in verifying the feasibility of a matching with respect to all constraints, and in efficiently determining the best improvements. The human analyst controls the evaluation and optimization by fixing initial parameters (including the weights of the criteria and the threshold values of prohibitions) and by adjusting and updating (parts of) the computed matchings.

BOAST can be used on two hierarchical levels: on an urban or regional level for evaluating and optimizing the housing of government organizations in the available buildings (in the following we will refer to this part of the system as BOAST I; in the GBA organization this part is referred to as BOSS), and on a building level for evaluating and optimizing the housing of departments of a government organization in the zones of the building, and of the housing of the employees of departments in the work-units of zones (this part of the system will be referred to as BOAST II, which in Dutch is called GIOS). BOAST is implemented in the C language on PCs which communicate with other systems of the GBA to obtain their information. The level I part of the system is implemented on a MAC system, but it runs under MS-DOS and UNIX as well. The level II part of BOAST runs under MS-DOS and UNIX.

The sequence of topics in this paper is as follows. In Section 2, the general approach of evaluating and improving matchings is described. In Section 3, the criteria which have to be taken into account are described in more detail. Section 4 contains a succinct description of a priority method which can be used to determine the weights of the criteria. The underlying ideas of the optimization algorithms are described in Section 5: this section may be skipped by (some of) the readers. Section 6 contains some practical results. The conclusions are presented in Section 7.

2. The General Approach

In using BOAST, the user proceeds as follows. First, the user of the system has to assign basic scores with respect to each criterion separately.

TABLE 1. A level I case

Organizations	
. Number	10
. Total required space	29537 m²
Buildings	
. Number	6
. Available space	32909 m²

Evaluation of current matching

Criterion	Weight	*	Criterion score		
Used space	16%	*	44.68%	=	7.15%
Concentration	52%	*	27.90%	=	14.51%
Location	0%	*	100.00%	=	0.00%
Housing cost/m²	16%	*	62.81%	=	10.05%
Ownership/renting	0%	*	87.85%	=	0.00%
Public transport	16%	*	49.25%	=	7.88%
					39.59%

Evaluation after optimization

Criterion	Weight	*	Criterion score		
Used space	16%	*	100.00%	=	16.00%
Concentration	52%	*	98.15%	=	51.04%
Location	0%	*	100.00%	=	0.00%
Housing cost/m²	16%	*	66.62%	=	10.66%
Ownership/renting	0%	*	87.85%	=	0.00%
Public transport	16%	*	53.25%	=	8.52%
					86.21%

On level I, a basic score has to be assigned, for example, to each organization with respect to the criterion 'used space', which measures the extent to which the used space of the organization is in accordance with the standard. For example, the basic score of an organization with respect to the criterion 'used space' might be 100% if the assigned space deviates less than 1% from the standard, or 80% if the deviation is between 1% and 5%, etc. Next, the basic scores are aggregated to criteria scores by addition of the basic scores (see Tables 1 and 2). If it is relevant, the basic scores are weighted, as in the aforementioned example, where the basic scores are weighted with the size of the organizations. Then, in step 3, these criteria scores are aggregated to a total score of a matching, where each criterion score is weighted by a criterion weight, which has to be specified by the user of the system. These weights, which measure the relative importance of the criteria, can be determined by a pairwise comparison technique from the priority theory (Boender et al. 1989; see also Saaty 1980). These total scores, in combination with their decomposition in criterion scores, provide the information to analyze and evaluate matchings (see Tables 1 and 2). Finally, matchings can be optimized by moving (parts of) organizations and/or departments from one building and/or zone to another, in such a way that the total score of the resulting matching is maximized, taking into account certain conditions which matchings have to satisfy and the cost of moving. To carry out the optimization, the system invokes optimization algorithms from Operations Research (see, for example Nemhauser et al. 1989; Heyman and Sobel 1990), as will be described later.

To illustrate the general approach, we refer to the Tables 1 and 2, which we will describe in more detail below. The first part of Table 1 describes a multi-criteria evaluation of a matching of a number of organizations in a large Dutch city. The second part of this table describes the evaluation of the new matching which would result if the movements would be carried out which are computed by the level I optimization algorithm. Table 2 describes the results of the application of the level II optimization algorithm to allocate the employees of an organization to the work units of a new building.

3. The Criteria

3.1. LEVEL I CRITERIA

On an urban and regional level more than 20 criteria are considered, distinguished as so-called matching and technical criteria. The matching criteria measure the extent to which the organizations are accommodated in correspondence with their various requests and demands. Some relevant examples of these criteria are 'used space', 'concentration', and 'location'. The criterion score with respect to 'used space' measures the extent to which the space assigned to organizations is in accordance with the standards, which are set on a strategic level. Thus, if a high weight is assigned to 'used space', the total score of a matching will to a large extent be determined by the quality of the matching with respect to this criterion. Also, a high weight will clearly force the optimization algorithm to search for a new allocation in which the spaces assigned to the organizations are in accordance with the standards as much as possible (taking into account the remaining criteria as well). However, 'used space' is one of the examples of the criteria which also serve as prohibitions, since too large deviations (to be specified by the user) from the standards are not allowed. These prohibitions typically become active in the optimization process, where they impose restrictions on allowable movements to improve the total score. For each organization the criterion score with respect to 'concentration' is positively rewarded if the organization is concentrated in only one building. In the optimization process a movement which results in a deterioration of the scattering of any organization over buildings is not allowed. The concentration criterion is analogously applicable to groups of organizations which have to be concentrated in one building. The criterion score with respect to location measures the extent to which the organizations are located in accordance with the city area (e.g. city centre or suburb) they prefer.

TABLE 2. A level II case

Organization	
. Number of departments	7
. Number of solitaries	50
. Number of non-solitaries	384
. Total required space	4444 m^2
Building	
. Number of zones	33
. Number of work units	481
. Available space	5197 m^2

Optimization results	
. Number of generated matchings	400
. Computation time (80386/33 MHZ with mathematical coprocessor)	10 min.
. Estimated probability of a better matching	0.5 %

Criterion	Weight	*	Criterion score		
Used space	10%	*	99%	=	9.9%
Connectedness	30%	*	100%	=	30.0%
Number of floors	30%	*	30%	=	9.0%
Relations	30%	*	100%	=	30.0%
					78.9%

The technical criteria are used to take into account strategic housing goals. Some relevant examples include housing cost, ownership/renting, and public transport. Housing cost (per m^2) of a building is included because GBA's task is to reduce the housing cost by 10% per employee. If this criterion is given a high weight, the total score will largely be determined by the housing costs of the matching, and the optimization algorithm will enforce movements to the most economical buildings. Ownership/renting is included in order to ensure that sufficient buildings are rented rather than owned, which increases flexibility, and the 'public transport' criterion reflects the government policy on the advancement of public transport and the reduction of the use of cars by commuters.

3.2. LEVEL II CRITERIA

At the building level 'used space', 'connectedness', 'number of floors', and 'relations' are taken into account. Analogous to level I, 'used space' measures the extent to which the space assigned to employees is in accordance with the standards. Furthermore, on level II the space which is assigned to a department is not allowed to be less than its standard. The 'connectedness' criterion measures the degree to which departments are housed in connecting zones. The criterion is obviously introduced to prevent the scattering of departments over a building. Analogous to 'connectedness', 'number of floors' measures the extent to which departments are housed on a minimal number of floors, and 'relations' is included to take into account that for some departments it is relatively important to be positioned in the neighbourhood of other departments, or in the neighbourhood of special zones of a building. In the determination of optimal allocations of departments to zones, and of employees to the work units of a building, several other restrictions have to be taken into account as well. These may include a maximum number of work units of office rooms, and the obligation that solitaries (i.e., people working alone) have to be allocated to a single room.

4. A Pairwise-Comparison Priority-Theory Method

To determine the weights of criteria, the user can apply a priority-theory method. The method infers the weights of the criteria from pairwise comparison of the criteria. For example, an analyst might judge 'concentration' to be three times as important as 'used space', and he/she might judge 'housing cost per m^2' and 'public transport' to be equally important. The method uses these pairwise comparisons of (possibly more than one) analyst to determine the weights of the criteria by logarithmic regression. Thus, if r_{ijk} denotes the evaluation of criterion i relative to criterion j by the kth analyst ($k=1,\ldots,m$), the weights $w_1,\ldots,w_n$ of the criteria are determined by minimizing the regression function

$$\sum_i^n \sum_j^n \sum_k^m \ln\left(\frac{r_{ijk}}{w_i/w_j}\right)^2 = \sum_i^n \sum_j^n \sum_k^m \{\ln(r_{ijk}) - \ln(w_i) + \ln(w_j)\}^2. \qquad (1)$$

That is, the weights $w_i,\ldots,w_n$ are determined such that the sum of the (squared logarithmic) deviations of the pairwise comparisons r_{ijk} from the (unknown) true values w_i/w_j is minimal. (The logarithmic transformation is partly motivated by the desire to obtain a decision problem which is linear in the decision variables $\ln(w_i)$.) For details the reader is referred to Boender et al. (1989).

5. The Optimization Algorithms

In this section we give a short description of the ideas underlying the developed optimization algorithms. The level I optimization algorithm is designed to optimize a current matching. Starting from a current matching, a new matching is determined which maximizes the total score (see Step 3 of the general approach), taking into account the restrictions, such as the prohibition to reduce the concentration of organizations, and taking into account the cost of movement. The level II optimization algorithm determines an optimal matching of the employees of an organization with the work units of a building, not taking into account their current positions in the building (if any).

5.1. THE LEVEL I OPTIMIZATION ALGORITHM

Starting from a current situation, the level I algorithm applies a so-called two-exchange heuristic to construct improvements (Lin 1965). First, a pair of units is selected, whereby a unit is defined as the part of an organization which is housed in a certain building. Thus, in an ideal matching the number of units would obviously be equal to the number of organizations. For the considered pair of units, the optimal allowable allocation of the two (parts of) organizations to the two buildings of the pair is determined. That is, the number of square metres which have to be assigned to each of the two organizations in the two buildings is determined such that the total score of the new matching is maximized, and all restrictions are satisfied. Such an improvement can be realized by (combinations of) the following actions: *Adaptation* (a reduction or increase of the number of square metres of an organization in the building where it is already positioned), *Transfer* (a move of an organization from one building to the other building), and *Exchange* (a move of an organization from one building to the other building, where its vacancy is, possibly partly, filled up by the arrival of the organization from the other building. After the determination of the optimal repositioning of the two organizations in the two buildings, it is checked whether a further improvement can be realized by the adaptation of the used space of the other organizations in the two buildings. These adaptations might be possible due to resulting vacancies of the repositioning. This step is carried out for each possible pair of units. If no permitted repositioning turns out to exist, the algorithm is completed, otherwise from all the possible repositionings, the one with the best total score which is permitted with respect to all constraints is chosen. This repositioning is carried out to obtain a new matching, and the whole process is repeated until no permitted repositioning exists. Note that the algorithm in each iteration for each unit considers each possible move to another building, as well as each possible 'return move' to fill a resulting vacancy (which is practically impossible for a human analyst). Nevertheless, in an efficient implementation each iteration takes less than one minute on an 80386 PC, even for large practical situations.

5.2. THE LEVEL II OPTIMIZATION ALGORITHM

The level II algorithm does not start from a current matching. Instead it assumes an empty building in which the employees of an organization have to be positioned such that the total score is maximized, taking into account all the relevant constraints. In order to accomplish this, first in step 1 (the *global phase)* a 'general' matching of the departments of an organization with the available zones of the building is generated. Next, in step 2 (the *local phase*) a 'detailed' matching of the employees with the work units of the zones which have been allocated to the departments in Step 1 is determined. If no such allowable detailed matching can be constructed, another general matching is generated. Otherwise, in step 3 (*stopping rule)* the best detailed matching is saved. This process is repeated until the estimated probability that a better matching can be found is less than a pre-specified value (say 0.5%).

The idea of iteratively applying a global phase and a local phase is generally accepted as an efficient and effective approach to solve complex optimization problems. The approach of the global phase is as follows. Starting from a partly constructed general matching, the algorithm generates one of the departments which are not yet allocated, and positions the selected department in the zones of the building which are adjacent to the zones which are already occupied. The selection of the department to be added to the partial matching, as well as the selection of the zones adjacent to the partial matching, occurs at random, where the selection probabilities are proportional to the expected attribution to the total score. That is, an extension of the partial matching which leads to a higher expected improvement of the total score has a greater probability to be carried out. In the local phase, the employees are allocated to the work units of the rooms of the zones which have been assigned to the departments of the employees in the global phase. This is accomplished taking into account all the restrictions which are mentioned in Section 3, such as the maximal number of work units of office rooms, and the obligation that solitaries have to be allocated to single rooms. In this phase we apply exchange heuristics as described above, and an adaptation of the first fit-decreasing rule, which is frequently used to solve the classical bin-packing problem (see Coffman et al. 1984).

In practice, the level II algorithm may iterate hundreds or thousands of times. The corresponding computation times (on a 80386 or 80486 PC) vary from a few minutes to many hours, depending on the size of the problem. The problem may embrace thousands of work units and several other factors, such as the relation between available and required space. In contrast with the level I algorithm, one is never sure if the level II algorithm has obtained the best possible result; each new iteration may lead to a better matching than the one obtained so far. Therefore, we applied recent results from the extreme value theory (see Dekkers 1991 and Dekkers et al. 1989). These can be applied since at each iteration of the algorithm each possible matching has a certain probability of being generated. Applying these results, we compute at every iteration of the algorithm the estimated probability that there is still a better matching than the best one obtained so far. This information can be employed by the user of BOAST to decide if the algorithm should be terminated or not.

6. Practical Results

We applied the BOAST system to several cases. The results of two of these cases are depicted in the Tables 1 and 2. The first part of Table 1 describes a multi-criteria evaluation of a matching of a number of organizations in a large Dutch city. The criterion scores are defined on a scale from 0% to 100%. Thus, the total score is defined on a 0%-100% scale as well, from which it can be concluded that the initial matching scores poorly (40%). Note from the table that the low score is primarily due to the fact that the organizations are weakly concentrated (a criterion score of 28% and a weight of 52%).

From the second part of Table 1 it can be concluded that the optimization algorithm yields an enormous improvement of the total score from 40% to more than 85%. Not surprisingly, this result is mainly determined by the improvement of the 'concentration' of the matching. To obtain this new situation, three adaptations have to be carried out, as well as one transfer and one exchange: the total number of square metres which have to be moved is 3480. For reasons of comparison we also computed a new housing situation taking into account the cost of moving. Then, a total score of 84% results, with two adaptations and one transfer, and only 480 square metres to move.

Table 2 describes the results of the application of the level II optimization algorithm to allocate the employees of an organization to the work units of a new building. In about ten minutes the algorithm determines the optimal location for each of about 400 employees in a new building. The total score of 78% indicates that the organization and the building match reasonably. The deviation from a score of 100% is clearly a result of the fact that (some of) the departments of the organization are scattered over more than one floor. The user of BOAST can employ the system to improve this phenomenon, but only at the expense of deteriorating the scores with respect to the other criteria.

7. Conclusion

In our opinion, the multi-criteria method and optimization algorithms, in combination with their implementation in BOAST, improves and structures the process of analyzing and optimizing the matching of demand and supply of building accommodation. The possibility to evaluate a matching with respect to several criteria (whose establishment required long and intensive discussions) clearly increases insight in the current situation. Furthermore, by varying the weights of the criteria and/or by adding (possibly imaginative) new buildings, several new matchings can be generated, which are optimal from different angles of incidence. From these optimal new matchings, the user him/herself can select a best admissible one, possibly on the grounds of considerations which are not taken into account by the system.

However, the authors realize that much work remains to be done. One important example is taking into account explicitly the (uncertain) long-term demand for accommodation. Another is the possibility that the system itself determines a building (or a reconstruction of an existing building) which minimizes the deviation between the quantity and quality of supply and demand of housing accommodation.

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