The Use of the Generalised Knapsack Problem in Computer Aided Strategic Management

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Abstract: There are many methods and tools in the literature that are helpful in strategic management. Some of them are related to the aspect of sustainability in terms of controlling and balancing the level of fulfilment of the different, sometimes conflicting, objectives which must be considered while building strategies. These tools include product portfolio methods. However, their use is often intuitive and detached from the quantitative aspects of management, such as cost-related restrictions or other quantitative restrictions imposed by the market or by internal circumstances. This article presents a proposal for the modification of portfolio methods aimed at enforcing the portfolio's quantitative aspect through the use of a discrete optimisation problem, namely the knapsack problem. Interacting with the decision maker, the quantitative parameters of the situation and the strategic goals are determined. Following this, a proposal solution is generated by a computer system in which the respective algorithms for the generalised knapsack problem (also called the generalised assignment problem) are embedded. The decision maker can accept the solution or change the parameters if the solution does not suit them or if they simply want to have other solutions for comparison. The outline of the system and the interaction between the decision maker and the system is illustrated by means of an example of constructing strategies for a university.

1 INTRODUCTION

There are many portfolio planning and control methods (also known as the growth–share matrices) in the literature. These methods help to control and specify companies' current and future market position and generally help to make strategic decisions. They make it possible to assess the directions in which organisations may develop; in particular they help to control which products, technologies, or strategic units the company should concentrate on and which ones should be abandoned or treated with less attention. This analysis is a good basis for strategic planning.

The idea of the application of the matrix methods consists of defining several (approximately 4–20) areas in the plane and identifying which areas the objects to be examined (they may be products, customers, departments, branches, etc.) belong to for the time being. Next there is the question of ranking the areas on the basis of a multicriteria analysis. Obviously, the areas that have the highest position in the ranking are usually preferred. Then, the decision maker should decide whether he or she is happy with the current distribution of the objects. The answer is usually negative. To address this problem, the decision maker has to identify which objects could and should be moved into which areas and which objects could and should be abandoned (i.e. taken out of the matrix (and thus the organisation) completely) so that the overall situation of the organisation with respect to the specified criteria becomes better than it was at the control moment, while the circumstances in which the organisation is operating are respected.

The practical application of the matrix methods is usually detached from its quantitative aspect and is rather intuitive. Not taking the quantitative aspect explicitly into account may prove decisive to the credibility of the control and of the selection of available possibilities for improving the current

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situation of the organisation. In particular, the aspect of the cost of potential actions to be taken and its relation to the projected budget for said actions may have a decisive influence. Moving objects into “better” areas requires concrete actions and creates cost –as may moving objects into “worse” areas (to make room for other objects), removing objects from the matrix (i.e. from the organisation), or making an object stay in the same area in the next period. The actions are also usually limited by several quantitative restrictions of an internal or external nature. These restrictions might, for example, be due to the fact that a good area will not accept any more objects, as the market is saturated. There may also be a restriction related to certain types of actions for which the organisation may only have a limited quantity of financial or human resources. Only attempting to take these restrictions into account in an intuitive way may mean that the optimal solution (according to the optimality criteria defined by the decision maker) is not always determined.

On the other hand, as the application of the matrix methods in fact reduces itself to answering the question of how to “pack” the available objects into the various areas in the matrix in an optimal way, it seems natural to combine the application of the matrix methods with the quantitative optimisation problem of packing, and more exactly with that of packing several knapsacks (backpacks). This combined proposal, together with the concept of a computer system which would support the decision maker in the control of the current situation and in strategic decision making, in which the quantitative restrictions and requirements may be introduced and interactively modified, is the main product of the paper. To illustrate the proposal, its application to the control and to the elaboration of a modification proposal of a university’s situation is described.

The outline of the paper is as follows. In Section 2 we briefly describe the main matrix methods. In Section 3 we present the optimisation problem used: the generalised knapsack problem (also called the generalised assignment problem) in the form in which it can be applied to the control of the organisation’s current situation and to the strategic decision making. In Section 4 we illustrate the combination of the matrix methods and the generalised knapsack problem as well as the concept of the computer system that supports the proposal by means of an application to a university’s situation. Screen shots are shown from the prototype of the system we have developed. The paper finishes with conclusions.

2 MATRIX METHODS USED IN STRATEGIC MANAGEMENT

The **Boston Consulting Group (BCG) matrix** (Udo-Imeh, Edet and Anani, 2012) is one of the best-known methods in portfolio analysis. The method helps to determine the strategic position of the company by indicating its possibilities for development. The idea of the BCG method involves the controlling and planning of a product portfolio or a portfolio of services in order to ensure a long-term balanced relationship between the products/services that are characterised by high competitiveness and profitability as well as new products/services, often in the development phase, which are not highly competitive or profitable. The BCG matrix helps to determine which products should be withdrawn from the range of production and which should bring more profit in the future (Fig.1).

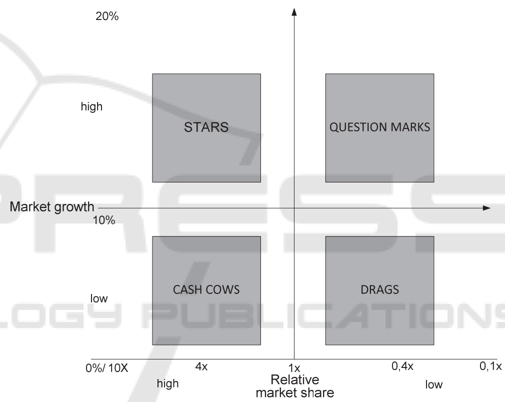

Figure 1: BCG matrix (Adapted from (Porth, 2003)).

As shown in Fig. 1, the BCG matrix is based on two criteria–relative market share and market growth. The relative share of the market helps to evaluate the degree of competitiveness of the company. The second dimension relates to the attractiveness of the market in which the company operates. The two dimensions (criteria) define four areas in the matrix.

In the late 60s and early 70s, when the BCG method was first presented, the division between the high and low market growth rate was determined to be 10%, which is often diminished today to 5% (Udo-Imeh, Edet and Anani, 2012) and may be changed by the decision maker.

The second dimension – the relative market share – allows the decision maker to evaluate the competitiveness of the products and/or services. This indicator, because of its specificity, indirectly takes into account the competition, and, in contrast to the market growth rate, is measured in terms of current values. “Relative market share“ enables the competitive position of the company to be compared with its largest competitor, whose position determines the limit seen in the matrix. Products/services placed in Fig. 1 on the left side of the border reached a leading position in the market. For example, a share equal to 4 means that the sales of a particular product are four times greater than the strongest competitor.

The four areas in the BCG matrix define four product groups. The first group is called “Stars”, which represent a valuable investment and have a good outlook for the future. The second group of products is “Question marks” (also called “Problem children”), which are characterised by an unknown future. Just like “Stars”, these units are characterised by high market growth. However, the attractiveness of the market, high returns, and low entry barriers may allow the competition to gain strength. This situation requires significant outlays in the fight with the competition, including marketing activities. A small market share may be the reason for the late introduction of these products to the market. “Question marks” are unprofitable products that require funding from other sources. The third group of products, known as “Cash cows” (also called “Hosts”) is a group of profitable products with an established competitive position which generate a financial surplus that can be used to finance other product groups (especially those which currently do not generate profitability, but provide opportunities for development in the future). The low market growth rate associated with this product group makes the market less attractive to new investors. The company has wide discretion in determining the prices and quantities of products produced, but significant investments in the modernisation and improvement of products cannot be made. The last group of products are so-called “Balls and chains” (also called “Dogs” or “Pets”).“Dogs” do not generate high surpluses or incur significant capital expenditures. They are typically characterised by low profitability. They are not progressive and do not bring the profits expected of them (Wilson and Gilligan, 1992).

Factoring in these considerations, the user conducts a ranking of the four areas. Seeing the matrix with the present products located in the respective areas, the decision maker evaluates the current situation and plans to take, if possible, actions to move the selected products from one area to another one or make the effort the keep them in the area where they are or to take them out of the organisation completely. Thus, we are faced with the problem of packing four knapsacks in an optimal way; while the knapsack “Balls and chains” should of course be avoided, the other three knapsacks are more desirable. All these decisions may be limited by some quantitative requirements. The decision of where to put the limits that define the four areas (how to choose the thresholds for the two criteria) is of a quantitative nature. These requirements and preferences of the decision maker will be able to be taken into account explicitly in the quantitative model that we propose later in this paper.

Other matrix methods will be described in less detail. The **General Electric(GE)matrix**, also called the McKinsey Matrix or Business –Industry Attractiveness Matrix (Udo-Imeh et al., 2012), is based on the assumption that the company should operate in more attractive sectors and focus on investing in products that have a strong competitive position (Fig. 2).

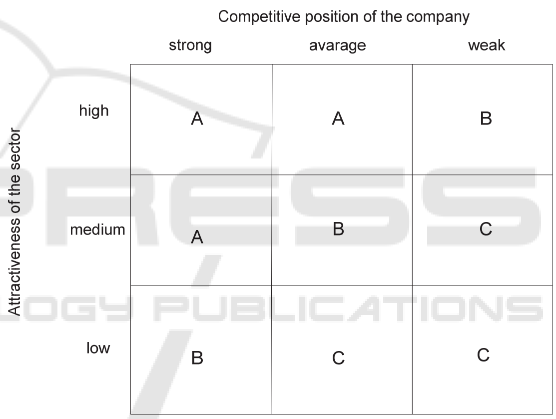

Figure 2: GE matrix (Udo-Imeh et al., 2012).

The GE matrix model is based on two criteria: the competitive position of the company and the attractiveness of the sector in which its products are offered. For each of the variables there are three options (high, medium, and low) of assessment provided. In this way 9 areas are distinguished in which products under evaluation may be placed. Symbols A,B, and C (Hax and Majluf, 1990) in Fig.2 represent a possible basis for the ranking of the nine areas (the areas marked with A form the group of areas with the highest ranking, followed by the areas marked with B, etc.), whose details will have to be resolved by the decision maker. All the areas marked with one letter may also form one area (one knapsack in our approach). Following this, the decision maker would have to resolve the optimisation problem of the optimal packing of the nine areas, where the areas ranked the highest would be preferred. Our proposition in Section 4 would help to formalise this decision and to find the best possible solution. The limits (the threshold for the criteria) may also be defined in a quantitative way, in which case our proposal would help to examine the sensibility of the various solutions to the decision of what the notions “high”, “medium”, and “low” are chosen to mean. Here fuzzy thresholds may be used.

The **ADL matrix**, also called the Maturity Matrix (Mason, 2010), helps to assess company products on the basis of two criteria – the competitive position of a product in the sector and the maturity of the sector. Five different competitive positions and four phases of the industry life cycle are distinguished, which gives 20 areas, usually grouped into three categories – A,B, and C – as in the case of the GE matrix.

The **Hofer and Schendel matrix (**Ionescu et al., 2008) is a development of the GE and the ADL matrix. Its authors suggest that the assessment of strategic units must take into account the size of their competitive position and the phase of the business life cycle that they are in. Hofer and Schendel also introduce other criteria in order to assess life-cycle phases, such as the embryonic, market entry, growth and shocks, maturity, and decline phases. They also propose various strategic options ranging from strengthening the market position, through finding a market niche, to withdrawal from the business.

The **Ansoff matrix** (Ansoff, 1957) focuses on the selection of strategic options based on the criteria of the market and product newness. Ansoff assumes four possible strategies for business development, i.e. market development, product development, market penetration, and product diversification.

To sum up the usage of matrix methods in the control of a company’s current situation and its strategic management, we can say that various criteria and criteria threshold values are used in order to define areas which we can see as knapsacks (backpacks).These knapsacks are filled in in the given moment in a certain way (each product or each customer belongs to one knapsack). The objective of the decision maker may be – and usually will be – to change the assignment of individual objects to the knapsacks, as some of the knapsacks are considered to be better and some worse from the point of view of the overall situation of the organisation. Following this, the problem of the optimal packing of the knapsacks in a given situation is in fact considered, without being explicitly seen and formulated. It is usually solved intuitively, without explicitly considering the quantitative limitations. The approach we propose in Section 4 will make it possible to formulate an adequate quantitative optimisation problem, with the participation of the decision maker, and implement it in a computer decision support system, which allows better solutions (because they are formally optimal) to be obtained.

In the next section we will present the generalised knapsack problem, also known as the generalised assignment problem, in the form in which it should be used in our proposal.

3 GENERALISED KNAPSACK (ASSIGNMENT) PROBLEM IN PORTFOLIO ANALYSIS METHODS

The methods described in the previous section help to evaluate the current situation of an organisation’s products, customers, or departments and help users make decisions about how to improve their organisation’s current situation. However, in our opinion they would do this more effectively if the quantitative aspect, quantitative objectives, and quantitative requirements were incorporated explicitly into the methods. The optimisation problem based on the knapsack (backpack) problem with multiple knapsacks, also called the generalised assignment problem, might in our opinion constitute a useful basis for this step. An incorporation of this kind, together with a computer system that allows the decision maker to shape the formulation of the optimisation model according to his or her wishes, would constitute a considerable form of assistance in making strategic decisions.

In the single knapsack problem (Martello and Toth, 1990), we ask the question of which objects (each of them having a certain volume and a certain value) from a given set of objects can be put in the knapsack, so that their total volume does not exceed the knapsack capacity and their total value is as high as possible. If we have several knapsacks (the problem is then called the generalised knapsack (assignment) problem (Haddadi and Ouzia, 2004)), the value of each object may depend on the knapsack it will be placed in. Next, this assignment of objects (some of which may remain unassigned because of a lack of knapsack capacity) to the knapsacks is explored to determine which assignment would maximise the total value of the objects placed in the knapsacks while not exceeding the capacities of the knapsacks and respecting other constraints. Such an optimisation problem suits our needs well. We have various knapsacks–various areas in the matrices, each of which may give another value to the object placed in it. The volume may be represented in our case by cost, which would be generated by the decision to move the item from one knapsack to another, and, if so desired by the decision-maker, by the decision to leave an item in the knapsack. The limitations (the equivalent of the knapsacks' volumes) would be the budget available for implementing strategic decisions or some other limits. For example, we might have a limited budget or limited competences for certain types of actions (e.g. promotion actions). The equivalent of volume may also be simply the number of objects. This would be the case if the market did not allow a matrix area to absorb more objects than a certain number. All constraints of this type and many more could be introduced into the model and modified if necessary in cooperation with the decision maker. The model presented below and implemented in the computer system prototype we present in the next section can be expanded in many ways, including the introduction of fuzzy divisions between knapsacks/areas and other soft (fuzzy) elements.

The basic model, based on (but not identical to) the generalised knapsack problem, would be as follows: we assume that in the matrix we have M areas or domains, denoted as $D_j, j = 1, \dots, M.$ Each area has a certain ranking position in the eyes of the decision maker, denoted as $R(D_j), j = 1, \dots, M$, while function R does not have to be injunctive. There are also N objects $O_i, i = 1, \dots, N$. If object $O_i$is in area D_j, it has value v_{ij}, where this value is determined by experts and takes into account the ranking of the domains. In some cases we may simply have $v_{ij} = R(D_j), i = 1, \dots, N, j = 1, \dots, M.$ We also assume that we have a function that evaluates the overall situation of the organisation at a given moment, called the satisfaction function (*SF*), which we assume to be as follows:

$$SF = \sum_{j=1}^{M} \sum_{i=1}^{N} v_{ij} x_{ij} \quad (1)$$

where x_{ij} is the binary variable that takes on a value of 1 if the *i*-th element is in the *j*-th area, and takes on 0 if otherwise.

At the moment of the control of the organisation's current situation, the decision maker has to identify the area that each object belongs to at that moment and calculate the current value of function(1). If the value of function (1) is satisfactory, there is no problem to be solved. However, if it is not, we change the meaning of variables x_{ij}. They turn into decision variables: x_{ij} is equal to1 if the *i*-th element should be placed in the *j*-th area, and equal to 0 otherwise. For $O_i, i = 1, \dots, N$, the decision maker has to determine which areas it might be moved potentially to, and evaluate for each area the cost of moving object O_i into area $D_j, j = 1, \dots, M$or of keeping it in this area. This cost will be denoted as $c_{ij}, i = 1, \dots, N, j = 1, \dots, M$. If object $O_i$cannot be moved into area D_j or the decision maker wants to forbid such a move, then $c_{ij}$is given a very high value. Function (1) becomes an objective function which should be maximised.

We will have in the model the basic constraints of the generalised knapsack problem (Martello end Toth, 1990), assuring that no object is placed in more than one knapsack. The equality sign is also possible, if we require all the objects to be in one of the domains, thus if we do not want to eliminate any object from our activity:

$$\sum_{j=1}^{M} x_{ij} \le 1 \text{ for } i = 1, \dots, N \quad (2)$$

On top of that, all the budgetary or other resource limit-based constraints have to be identified. For example, if there is a budget B which can be used for the realisation of the strategy identified by the optimisation problem, we will have the constraint:

$$\sum_{j=1}^{M} \sum_{i=1}^{N} c_{ij} x_{ij} \le B \quad (3)$$

We might also have, for example, a budget $B_{i_0}$of all the activities related to object O_{i_0}(i_0 being one of the numbers $1, \dots, N$). This might happen, for example, in the case where each object has a budget assigned to it and no money transfers among objects are allowed by the organisation's management. Then we would have the constraint:

$$\sum_{j=1}^{M} c_{i_0 j} x_{i_0 j} \le B_{i_0} \quad (4)$$

Another type of constraint could be due to the fact that it is not possible to place more than a certain number of objects in a "good" area, as the market does not allow it. If the area in question has index j_0 and the limit is L_{j_0}, we will have the constraint:

$$\sum_{i=1}^{N} x_{i j_0} \le L_{j_0} \quad (5)$$

Constraints (4) and (5) might have further variations according to the wishes of the decision maker. Some of these variations will be illustrated in the next section.

The solutions of models (1) to (5), found by means of any software that provides solutions to integer linear programming problems (for example the free software "Gusek", [http://gusek.sourceforge.net/gusek.html]), will deliver the values of the decision variables, which in turn ensuring the highest possible value of objective function (1) in the given circumstances. If the decision maker is not happy with this value, he or she may consider modifying the model.

The following section contains an example of the application of the proposed concept to the strategic management of a Polish university. At the same time it shows screenshots of the prototype of the proposed computer system in which our proposal has been implemented.

4 APPLICATION OF THE APPROACH AND THE COMPUTER SYSTEM CONCEPT

The example discussed here concerns a Polish university. The university faculties (there are seven of them, denoted by $W_t, t = 1, \dots, 7$) will be the objects of the analysis and of the strategic decisions. They can be assessed from the point of view of different criteria. In the discussed case, we propose the use of two criteria, i.e. the attractiveness of the faculty and its profitability (other criteria would be also possible).

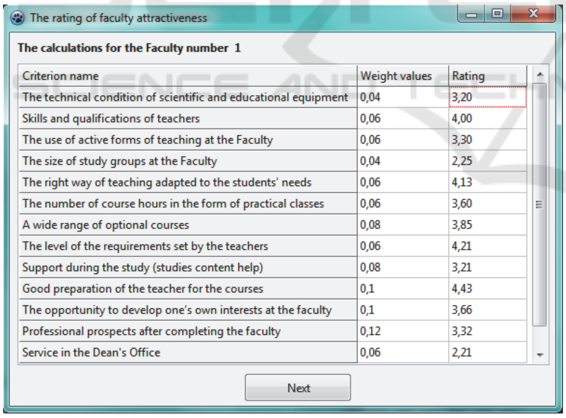

Figure 3: A screenshot showing the assessment of one faculty's attractiveness.

While profitability is a rather unanimous measure (although there are serious problems linked to university costing (Cox, Downey and Smith, 1999; Klaus, 2008; Klaus-Rosińska and Kowalski, 2010)), attractiveness may be measured using various criteria and from various points of view, which have to be aggregated in a certain way, e.g. by means of weighting. Figure 3 gives an idea how this can be done in the computer system we propose.

We do not enter into details here, although more on the subject of faculty attractiveness assessment can be found in (Ryńca, 2014).Here we give the final results of the calculations:

Table 1: Assessment of the university faculties.

No	Criteria	Faculty						
		W_1	W_2	W_3	W_4	W_5	W_6	W_7
1	attractiveness	3,46	3,44	3,10	3,28	3,56	3,80	3,42
2	profitability	138,6	60,2	68,1	89,9	45,8	19,3	101,56

First, the current university situation was subject to a control. In the prototype of the computer system, in which *M*=4 and the threshold values were chosen by the decision maker, taking into account Table 1, we can see the following screen, where all the faculties have been placed in one of the four areas, illustrating the current situation of the faculties:

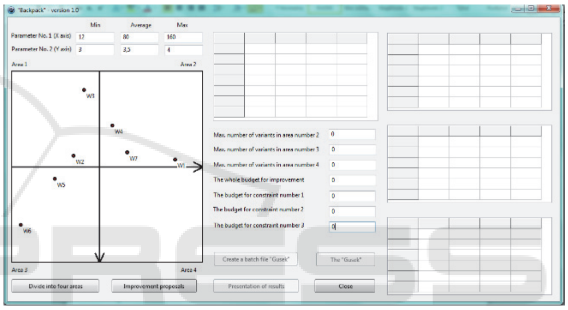

Figure 4: A screenshot showing the positions of the faculties.

The profitability of the faculties is marked on the X axis (the horizontal axis), while the attractiveness of the facilities is displayed on the Y axis (the vertical axis).

Function *R* was entered (*R*(1)=0, *R*(2)=4, *R*(3)=5, *R*(4)=8), and it was assumed that $v_{ij} = R(D_j), i = 1, \dots, 7, j = 1, \dots, 4$. The current value of objective function (1) was calculated and found to be equal to 22. The maximum possible value of (1) (in the ideal case where all the faculties are in the 4th area) is 56. The relation of 22/56 was found to be unsatisfactory. Thus, the decision maker was asked to use one of the empty matrices in Figure 4 to define the cost of all the transfers possible and desirable for the departments between areas. It was assumed that keeping a department in an area where it was at that moment would not generate any cost and that transfers to lower-rated areas were not allowed. The results entered by the decision maker are given in Table 2.

Table 2: Cost of actions which would move a faculty to a higher-ranked area.

Faculty W_i	Cost of moving W_i to Area 1	Cost of moving W_i to Area 2	Cost of moving W_i to Area 3	Cost of moving W_i to Area 4
W_1	----------	0	40	50
W_2	0	10	20	30
W_3	0	20	20	25
W_4	----------	0	10	10
W_5	----------	----------	0	60
W_6	----------	----------	0	70
W_7	----------	0	40	60

Later, several constraints of the type discussed in Section 3 were introduced (the basic knapsack problem constraints (2) are included in the model automatically). All this can be seen in the next screenshot of the computer system (see "Cost matrix"):

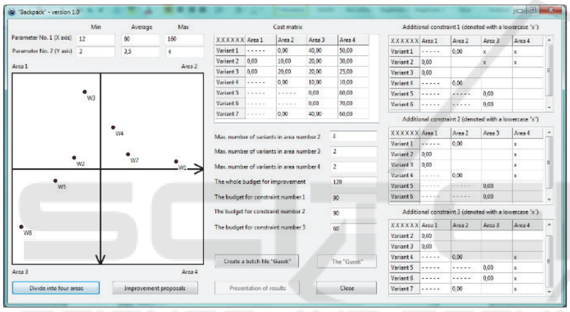

Figure 5: A screenshot showing the costs of the transitions between areas including additional constraints.

The additional constraints seen in Figure 5 are:

- one concerning the total budget for improvement actions (3)
- those concerning limited budgets for groups of actions, crossed in the matrices on the right-hand side of the screen, of type (4) (e.g. constraint number 1 is $40x_{13} + 50x_{14} + 20x_{23} + 30x_{24} \leq 90$)
- those concerning the absorption possibilities of the individual areas (of type (5)).

Then a "Gusek" file with the integer linear programming model is automatically created, exported, and solved The solution, visible in the right-hand side of the screen in Figure 6, is then imported and shown to the decision maker in the system (Figure 6):

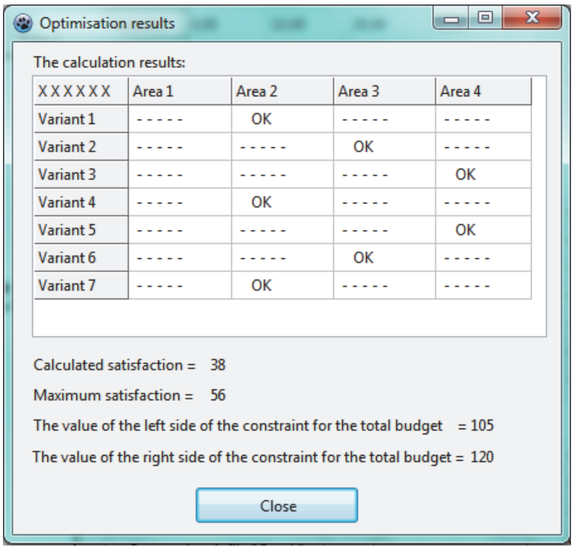

Figure 6: A screenshot showing the optimal solution.

The decision maker can see that it is possible to improve satisfaction with the university's position from 22 to 38, thus from 39% of the ideal satisfaction to 68%. The total budget for improvements will only be partially used (due to the other constraints – out of 120 monetary units available, only 105 are needed). The transfers that should be implemented are marked with OK in Figure 7. Thus there would finally be no departments in area 1, which is ranked as the worst area, departments W_1, W_4, and W_7 would be in area 2 (where they were before), departments W_2 (currently in area 3) and W_6(currently also in area 3) in area 3, and department W_3(currently in area 1) and W_5 (currently in area 3) would be in the best area, area 4. If the decision maker is satisfied with this solution, he or she may agree to it; otherwise, the model may be modified.

5 CONCLUSIONS

This paper proposes the calculation of matrix models known from strategic management, which support the evaluation of products, units, clients, or units of organisations, with a quantitative component using discrete optimisation methods, and proposes embedding all of this into a computer decision aiding system, allowing the decision maker to find the best solution according to his/her criteria. The use of mathematical models by decision makers forces a deeper reflection and a more systematic analysis aimed at a quantitative assessment both of the parameters of the controlled objects, as well as of the costs of various activities which may be undertaken to implement the adopted strategy. Even if the quantitative assessment is difficult in some cases, it fosters an objective analysis. In the case where crisp values are difficult to give, fuzzy numbers (or even linguistic expressions, modelled by fuzzy numbers) can be used. The generalisation of the proposed concept to the fuzzy case would not be complicated and is foreseen in future research, as fuzzy versions of the knapsack problem are discussed in the literature and corresponding algorithms exist (Lin and Yao, 2001; Kuchta, 2002; Changdar, Mahapatra and Pal, 2015).

Undoubtedly, the proposed model requires further verification in practice and the computer system prototype requires a large amount of testing. Further extensions should also be taken into consideration, in particular the introduction of fuzziness.

As far as the computational aspect is concerned, it must be noted that the knapsack problem belongs to computationally difficult problems (Haddadi and Ouzia, 2004), which means that if it were to deal with a problem of a large size (usually measured by the number of evaluated objects) the generation of an optimal solution may take a long time (this time can even be hours long). If a given organisation has several thousand products and wants to generate an appropriate strategy for them, then the determination of the solution may take more time. However, there are numerous references in the literature proposing approximate algorithms for such cases, which are much quicker (Haddadi and Ouzia, 2004; Michalewicz and Fogel, 2004). Additionally, the control of a company's current situation and strategy building is not an everyday activity, so even if it takes more time, this is usually not a serious obstacle and the type of free software we propose for use in this matrix should be satisfactory for practical purposes in most cases.

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