System Dynamics and Decision Support in Complex Systems

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In the proposed paper, the relationship between system dynamics and systems thinking as well as the dilemma about hard and soft methodology are discussed from the general point of view. It shows that the main problem in the modelling of complex systems derives from the complexity of the systems themselves and not from the shortcomings of the particular methodology. The role of the subject in the modelling of a complex system is discussed. The article continues with the general simulation model of the business system described by Forester's system dynamics. The methodology is sufficiently abstract to allow a qualitative and quantitative analysis of system functioning through feedback loops. The multiple criteria function used for the evaluation of different scenarios was defined with the aid of a decision group using the group support system. The methodology was successfully tested on real cases.

Introduction

Complex systems are usually understood by intuition as a phenomenon consisting of a large number of elements organized in a multi level hierarchical structure where elements themselves could represent systems. The named complex is used just to point out the fact that the problem treated here can't be expressed only in hard (quantitative) relations but that most relevant values are qualitative. A description of the system depends on the specific goal and point of view of the researcher. Although this problem has been considered in the literature to date, there is no unique opinion on the influence of the observer in the process of modelling. The whole issue of System Dynamic Review Vol. 10 Numbers 2-3, were devoted to the problem of the methodology of complex system modelling. The diversity of the relevant method (Checkland and Haynes, 1994; Flood, 1994) known by different names, for example: system approach, system thinking or system dynamics, Soft Systems Methodology etc. motivated us to discuss this topic from a general point of view in order to highlight some similarities and differences among them. The present article is a general approach to the method of modelling the complex system from an epistemological and semantic point of view. The article continues with the general simulation model of the business system described by Forester's system dynamics. The multiple criteria function used at the evaluation of different scenarios was defined with the aid of a decision group using the group support system. The methodology was successfully tested on real cases.

The Epistemological Problem of Modelling

A system represents a whole consisting of parts and was the axiom for system philosophers. However, the general system theory (GST) and cybernetics, clearly pointed out the relevance of the order and structure of elements within a whole for its behavior. In cybernetics there is no ontological problem. On the manifestation level, the system is described as it appears, instead of as it is. By definition, we anticipate that the system consists of elements and is greater than its parts. An element is the smallest part of the whole necessary for system description, which can't or won't be divided further. The essence of the elements is very important from the epistemological point of view. From the general point of view system is defined by set:

$$S = (E, R) \qquad (1)$$

where $e_i \in E, i = 1,2,..n$ represents the set of elements and $R \subseteq E \times E$ the relation between elements. Construction of concrete systems requires some procedure $K(e_i) \in E$, knowledge, to identify the elements of the systems and theory $T(e_i, e_j) \in R$ to find the relationship between the elements. In other words, modeling represents the activity to describe our experiences by using one of the existing languages in the framework of a certain theory. In this way, our experiences also become accessible to others: they may be proven, confirmed, rejected, broadened or generalized. This paradigm can be stated (Kljajić, 1998) with a triplet (O, S, M). O represents the real object, original, independent from the observer, while S represents the researcher (subject) or an observer with his knowledge, and M the model of the object. Their relations in the process of analysing are shown in Figure 1.

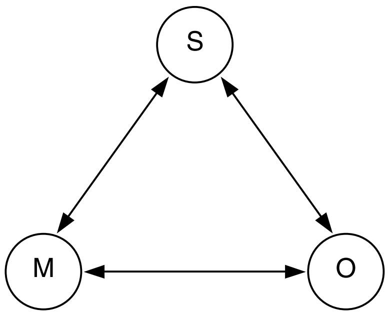

Figure 1: Subjects in the modelling process.

From Figure 1, a "naive realist" supposes that: 1. An external world exists independently of the observer, 2. This world isn't directly observable and 3. For its representation, we set up simplified models. The relation between the observer S and the object O - is of essential significance in the cognitive method. The observer is a man, with all his cognitive qualities, while the object of research is the manifested world, which exists by itself, regardless of how we can describe it. In this case, the object and the system have the same meaning. The third article of the triplet M is the consecutive one and represents a model or a picture of the analysed system O.The $O \leftrightarrow S$ relation in Figure 1, indicates the reflection of human experiences to concrete reality. This cognitive consciousness represents our mental model. The relationship $M \leftrightarrow S$ represents the problem of knowledge presentation, respectively the translation of the mental model into the actual model. The $O \leftrightarrow M$ relation represents the phase of model validation or proof of correspondence between theory and practice, which render possible the generalization of experiences into rules and laws. The $S \rightarrow O \rightarrow M$ relationship is nothing else but an active relation of the subject in the phase of the object's cognition. The $M \rightarrow O \rightarrow S$ relation is nothing more than the process of learning and generalization. A theory is an intellectual construction enabling us to give a more generalized form about the phenomena of the research to the directly obtained results from the experiment. In the cognitive process, the value standpoints of subject S_v are far more important to us in relation to the object of research in the modelling process. This can be stated in the following equations:

$$S_v \cap (O \cap M) = 0 \qquad (2)$$
$$S_v \cap (O \cap M) \neq 0 \qquad (3).$$

In the second part of the equation (1) and (2) $O \cap M \leq 1$ are always fulfilled. In the case of $O \cap M = 1$, the model and original are identical. The expression (2) is valid for formal and natural sciences, where $S_v = \varnothing$ (empty set). This means that it's impossible to find any link between the axiom and the hypothesis linked to model M and value standpoints of the subject. That is of course not valid for the scientific hypothesis in the process of modelling, which is always the product of the intellect and historically conditioned by the progress of science: these hypotheses are always rejectable (Poper, 1973). In the case of organizational sciences and humanities in equation (3) the value standpoints of the researcher and the object of the research are always $S_v \neq \varnothing$. Some qualities are always added to the description of the observer in question which are not provable. The conditions expressed by (2) and (3) have a key meaning in the choice of research methodology and for the scientific value of the statement. The first expression renders possible the setting up of the principle testable hypothesis by means of active experiments of the subject, while the second can't and is not allowed to prove the hypothesis through experiment, but by observation and generalization dependant on the qualities of the observer. In this light it is not difficult to find an answer to the dilemma in Richmond (1994), Lane (1994) and Forrester (1994) of what is broader, system dynamics or systems thinking or when to use hard or soft methodology? The answer lies in the problem itself, which needs to be solved and in what one understood with system dynamics or system thinking methodology.

Several methods have been developed for mathematical modelling of real systems. Each of them was motivated by the problem itself and the researcher in that field. System dynamics (SD), compartment model, block diagram and so on are most popular among them. In Cobelli et al. (1986) their similarities and differences were discussed. Practically both representations lead to the same equations. There are some symbolic differences in the graphic presentation of elements and their relationships. The system structure in SD consists of level elements representing state variables of the rate elements, representing the flow and the auxiliary elements connected in the flow diagram. The diagram is sufficiently abstract to allow a qualitative and quantitative analysis of the system functioning through feedback loops. As soon as one becomes satisfied with the "picture" of the model, he will proceed by writing equations of the simulation model. In our opinion, SD suggested by Forrester (1961) has some semantic advantage for users less experienced with formal methods. In a practice closely related to the SD methodology, some authors use a causal loop diagram or influence diagram (Eden, 1994). In this case, the influence loop diagram precedes the SD flow diagram because the former is more abstract while the second is more convenient for computer programming. This can be explained by expression (1). Let denote elements $e_i \in E,\ i = 1,2,..n$ with the node representing the state and connection $R \subseteq E \times E$ the branch and we will get a graph, which represents the picture of the system. This graph is equivalent to a causal diagram and represents a qualitative model of the problem to be solved. If we replace the node with a rectangle and branches with rate input and rate output, we will obtain a flow diagram of SD. The difference between the branches and rate is just in the degree of abstraction; the rate expresses the quantitative relationship measured in units while the branches express the direction of influence between the elements. To illustrate this difference, arriving from a level of abstraction, we will consider the well-known Malthusian law of population growth. Figure 2 shows an influence diagram, which represents a "picture" of a population model, while Figure 3 represents a flow diagram in SD methods, leading directly to a difference equation (4).

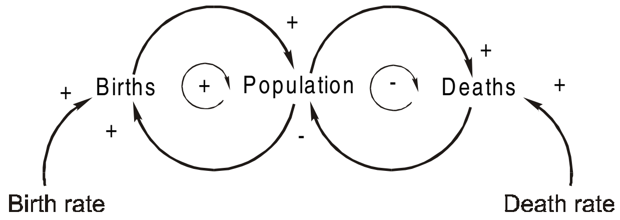

Figure 2: Influence loop diagram of population model

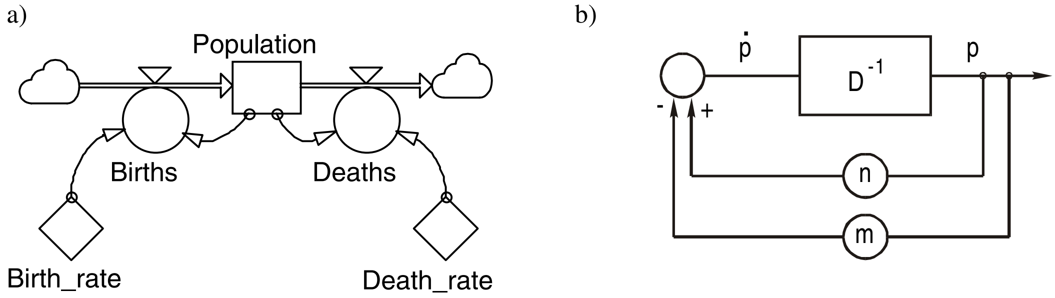

Figure 3: Different graphical presentation of population model:
a) SD flow diagram and b) block diagram.

$$p(k+1) = p(k) + \Delta t(np(k) - mp(k)), k = 0,1,2...N \qquad (4)$$

where n and m represent the birth rate and death rate respectively. n and m are time dependent coefficients. For n>m exp. growth and for n<m exp. decrease and only for n=m does the system reach equilibrium. If we limit $\Delta t \to dt$ equation (4) becomes the differential equation $\dot{p} = (n(t) - m(t))p(t)$ with a symbolic solution shown in Figure 3 b). Here, symbol D^{-1} represent integration block, which is equivalent to the level element in SD.

Decision Support Oriented Enterprise Simulation Model

In light of equation 2 and 3, three groups of the system can be identified: formal, natural and human. The formal system consists of abstract objects, where relations among them are based on a set of axioms. Natural systems consist of real objects where relations among them are founded by evolution. Knowledge about it, in principle, is accessible by experiment up to the Heisenberg's Principle of Uncertainty. Human systems or organization consist of different interactions between people and nature in order to realize certain purposes. Prior knowledge about system behaviour is limited and experiments are not allowed. Intuition is the main component of creation. The model of these objects represents a description of real objects in terms of an abstract system. How good and useful these descriptions are is the problem of model validation. From equation (3), the observed system is complex and its model contents subjective to assumptions of the observer. Such systems are open, dynamic and goal oriented (Ackoff, 1994).

From the decision point of view, the organizational system is defined as $S = (P, D)$, if mapping exists $P : X \times U \rightarrow Y$ and $D : X \times Y \rightarrow U$ such that, it is satisfied $G : X \times Y \times U \rightarrow V \in R$ and $E : X \times Y \times V \rightarrow U$, where *X* and *Y* represent the input and output of the system, *P* process, D decision process, *G* objective function and *E* evaluation strategy.

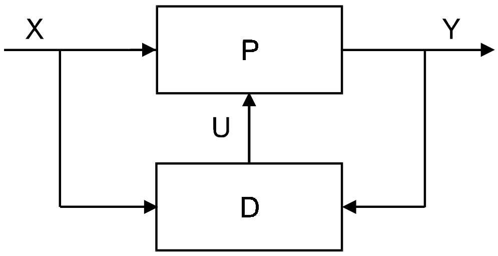

Figure 4: Universal model of goal oriented system

Note that *G* represents the objective of alternative, while *E* represents the subjective evaluation of decision. Consequently, decision in enterprise is not primarily concerned only with feedback dynamics (selecting of proper parameters of rate elements) but on rate elements matched with possible input into the system and prescribed criteria (Kljajić et al., 1998). As it is shown in Mesarović and Takahara (1989) that according to Arrow's Impossibility Theorem, it is not possible to find a democratic solution of social choice which will satisfy some socially acceptable conditions imposed on the decision problem. Arrow's axioms (1 to 5) are logically incompatible (Rapoport, 1986). The fifth axiom, which states the absence of a dictator (even in implicit form) is relevant in using GDSS.

The general simulation model of the business system has been described by Forrester's system dynamics. The system structure consists of level elements and parameters defining the rate and the auxiliary elements connected in the flow diagram. The diagram is sufficiently abstract to allow a qualitative analysis of the system functioning through feedback loops. As soon as someone becomes satisfied with the *picture* of the model, it will proceed to the definition of the simulation model. The state equation of the simulated system is described by the non-linear differential equation:

$$y(k+1) = f(y(k), s(k), a(k)); \; k = 0,1,2,..N \qquad (5),$$

where $y \in Y$ represents state variables such as inventory of material/products, cash, income, liabilities, backlog, etc., $s_i \in S$ represents the external input to the system (exogen scenario) and $a_j \in A$ represents the control vector (endogen scenario).

Decision strategy was defined as: for scenario s_i (state of nature) and its probability $p_i \in P$, find alternative a_j, which will solve the problem and satisfy the performance function, which reflects managers preferences. The results of the simulation are collected in a decision matrix, which represents the payoff of the strategy.

There are many different forms of the utility function. In actual case we considered two criteria: Expected value criteria defined by equation:

$$\max EV(a_j) = \sum_i C_{ij} p_i \qquad (6),$$

where C_{ij} represents the values of the i-th scenario at j-th strategy, and linear weighted sum of multiple criteria:

$$\max J(a_j) = \sum_{r=1}^{m} w_r J_r(a_j) \qquad (7),$$

where w_r represent the weight of the r-th objective, which reflects the decision maker's preference of business politics. The individual objective $J_r = q(y, s, a)$ is a function of the system state, state of nature and chosen alternative in achieving the goal. Satty's AHP method (Satty, 1990) was used to determine the relative importance of objectives w_r and pairwise comparison of alternatives a_j for the r-th objective.

The business simulation core consists of three parts: the basic model, modelled with the SD technique that represents the business process, program the scenario formulation, program for the analysis of simulation results and selection of solutions, and program for normative analysis. The simulation scenarios are made of two subsets: a subset of input that anticipate the impact of the environment (exogenous scenarios) or the state of nature, and a subset of management decisions that represent (endogenous scenarios). They give the answer to the basic question with regard to the problem situation for which the answer is being sought. In literature, it is known as the *what if, then, so what* analysis. The generation of scenarios of the simulation system that respond to the *what if,* is based on the variation of parameters of the basic scenario at the extrapolation of past behaviour and expert evaluation of development targets with the Brainstorming method. Variants of business scenarios are evaluated with the linearly weighted sum of the multi-criteria decision function. The complete simulation system for decision support consists of commercially available packages, for example: Powersim, ProModel, Group Systems, Expert Choice and Ventana Group Systems. The principal scheme of the system is shown in Figure 5.

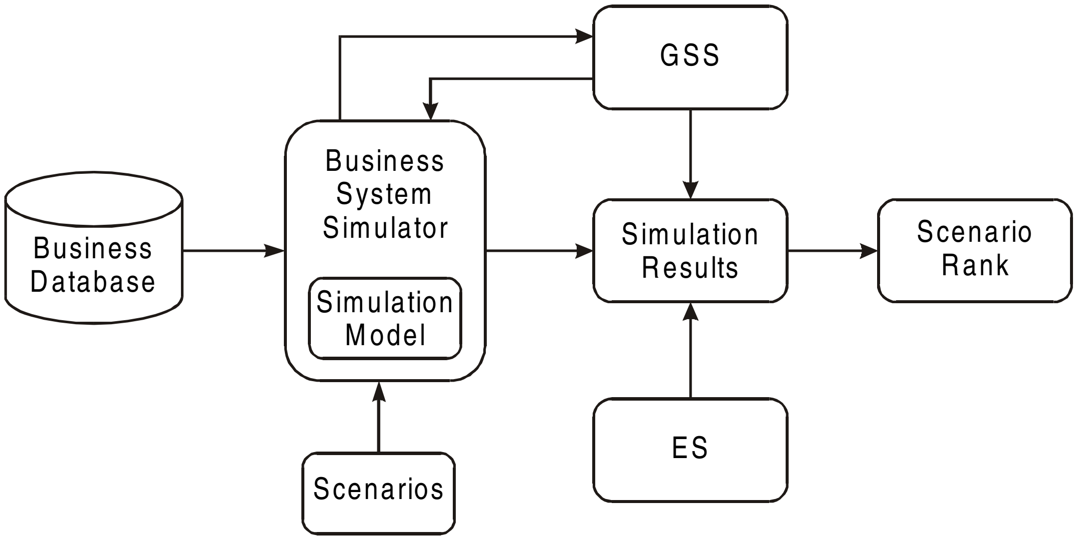

Figure 5: Decision support system structure

Results

Case 1: The objective of the study on the academic enterprises simulation model was to find the relevance of weighting factors of the multi-objective decision problem with GDSS in order to evaluate exogenous and endogenous scenarios.

Participants involved in the group decision experiment were last year graduate students. Three groups of students participated in the experimental sessions. Each group consisted of 15 randomly selected students. Subjects were recruited from a university level Decision Process Course. Students in the course were assigned to the groups at the beginning of the semester to cooperate in the sessions by the end of the semester after completing the course. The experiment started with a brief introduction to the business simulator application. Working with a simulator was simple and user-friendly. The user interface is based on classical Windows GUI, which allows participants to enter parameter values with sliders, input boxes and radio buttons. Participants can make variations of parameters in a permitted area and observe the behavior of the system. All of the user definable parameters were explained and tested in the course of the experiment. Basic scenarios were presented and the simulator response was verbally analyzed. To get better insight into the problem, an electronic brainstorming session was held as the starting point for the session. The next step was geared to the goal of scenario evaluation. Participants determined the parameters values of the business simulator as each individual saw possible business politics in order to get the sense of the model responses to different simulation scenarios. The session of criteria determination was open for debate among participants so that a common view could be established.

After experimenting on the simulator, the group determined important criterions. Gained ideas were categorized and ranked by the selected voting method. The experiment was continued on the simulator where predefined scenarios were presented. Basic simulation scenarios take into consideration the parameters of average price, material costs, desired inventory level and payment delay. The parameter of average price, for example, was used for simulating different market demands. There were five simulation runs executed for five simulation scenarios. All of the scenarios were also stated verbally. Actual scenarios were observed and compared with the aid of the simulator. The business simulation model was observed for 120 simulation days. Participants observed the dynamics of the different parameters in the simulator. This option was used for the analysis of different simulation scenarios. The graphs represent the course of time series of a chosen variable. Participants voted regarding the importance of scenario evaluation criterions in order to get the group evaluation of simulation scenarios. The evaluation was continued by using the linear multicriteria weighting function. Overall, criteria have been defined as the linearly weighted sum defined by equation (7). Decision groups have to determine the values of the weights w_i; $i=1, 2, 3, 4$ respectively. The results of separate criteria weighting by groups and the average value is shown in Figure 6. There is no significant difference between average and group estimation of weights. The average weighting value of the evaluation criteria revealed the next order: Profit / Sum Value of the Company Ratio, Profit, Inventory Value, Sum Value of the Company.

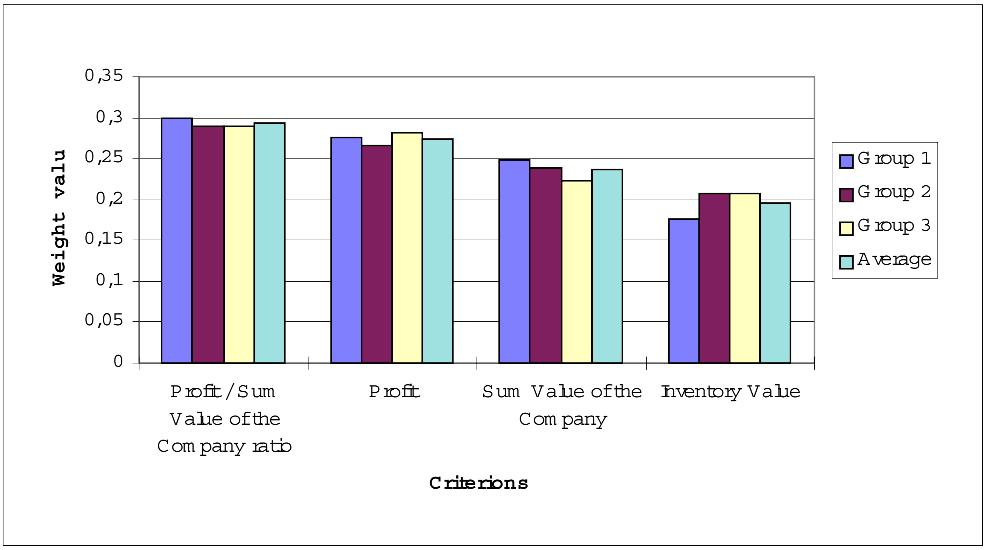

Figure 6: Group criteria weighting

The value of each objective for 5 scenarios has been analyzed according to the principle of the analytical hierarchy processes AHP, which ranked the scenarios in the following order: J_2, J_5, J_4, J_1, J_3 that would in the real case determine the business strategy for the evaluation period.

On the basis of the criteria weights, rank of the scenarios was determined. As a result of the decision making process, the best scenario i.e. the best parameter combination was selected using the group evaluation of criterions. The presented approach enhances decision processes by effectively exploring the methodology of system dynamics and group support systems allowing experimentation on business simulation models for the purpose of solving multiple criteria group decision problems.

Case 2: The described methodology was tested in a medium sized factory of concrete goods for reengineering assessment. Due to a raised demand for the article and better quality requirements of the products, the firm's management considered investigating a new production line. There are three suppliers besides the existing technologies considered for decision-making. Suppliers denoted as alternatives a_i=a_1,a_2,a_3,a_4 and their cost in many unit is: c_i= 0, 371, 392, 532 respectively. a_1 represent current technology.

Estimation of the state of nature s_i for the next 8 years and its probability are: s_1 - no change in market demands (15%); s_2 - medium increase of demands (40%); s_3 - high increase of demands (35%) and s_4 - medium decrease of demands (10%). The probability of the state of nature has been estimated by the application of the brainstorming method conducted in the meeting room and using GSS. Several requirements for the new technology were imposed: Quality of products, Net profit, Risk of company ruin, Market demands and Flexibility of technology.

With discrete event simulation models, we analyzed alternatives from a technological point of view for different conditions relevant for operative planning. A cost benefit analysis of alternatives was obtained with a continuous simulation model by using the system dynamic method. For each alternative, four scenarios representing the state of nature were prepared and simulated. The expected values of payoff for alternatives for an 8-year period were computed according to equation (2). C_{ij} is a function of: cost of investment, productions cost and market demands for i^{th} alternative and j^{th} state of nature. The results of evaluation are shown in Figure 7.

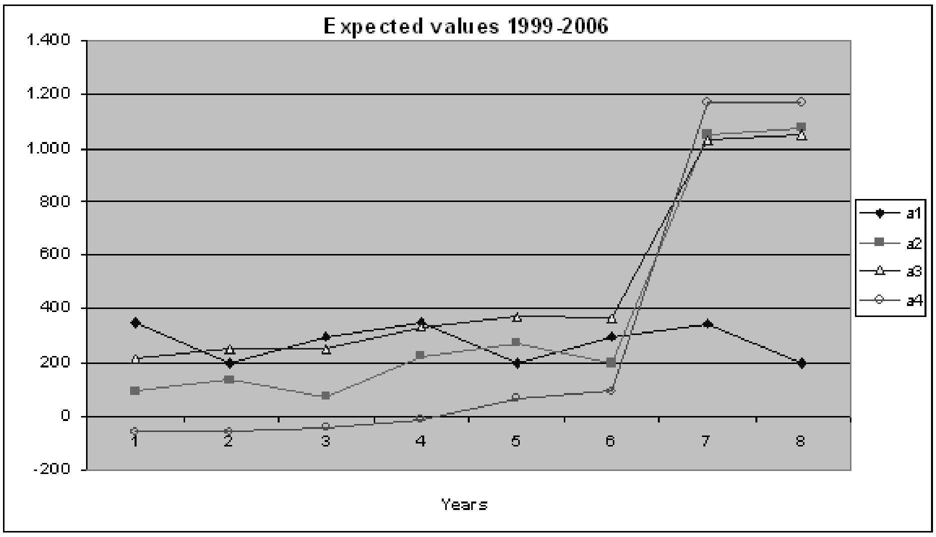

Figure 7: Expected value criteria in MU for the four alternatives as a function of time

The average expected value by alternatives for 8 years are shown in bar graphs in Figure 8. Because of the well-known shortcoming of the expected value criteria (subjective probability, uncertainty of expected value, etc.), users like to additionally examine the linear weighted sum of the criteria. Satty's Analytical Hierarchy Process - AHP Method was used for this purpose. In our case, there are three levels of hierarchy. On the first level, the goal L itself is placed. At the second level there are five criteria: Net profit, Quality of products, Risk of company ruin, Satisfying market demand and Flexibility of technology. The last level offers alternatives for ranking. It is necessary to choose the best alternative through the five criteria so as to achieve the overall goal. User gained information for their decision from the simulation of alternatives and discussions in the meeting room as well as from provider properties. Here, the full advantage of visual interactive simulation connected with the group decision support system in reengineering process was achieved. For example, the comparison of alternatives under the criteria Risk of company ruin was estimated using data from Figure 8. For this reason the preference of alternative a_4 through the Risk Criteria is less desirable. The decision horizon of 8-year use was defined by means of simulation methods. The results of multi criteria evaluation are also shown in Figure 8.

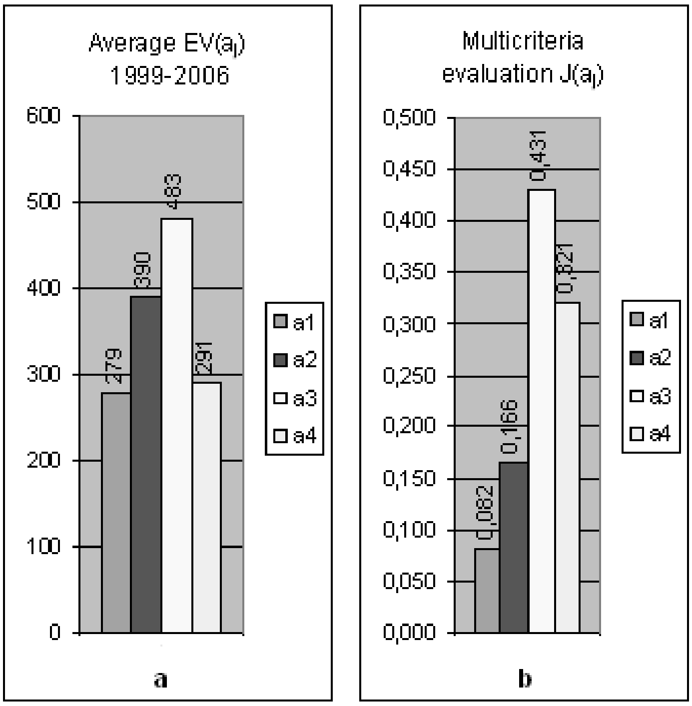

Figure 8: Bar Graph results of Expected Value and the AHP Method of four alternative evaluations.

The right graph shows the value of obtained alternatives: as a sum of products of weighted objectives with the value of alternatives. The alternative a_3 has the highest score according to the chosen preference. It is obvious that the a_3 alternative is most preferable in both criteria. Of course, such coincidence is incidental and a result of direct analyses. In the case where two different criteria gave different results, the simulation method together with GDSS is an excellent tool for group judgment about alternatives through simulation in different conditions.

Conclusion

In this paper, the relationship between system dynamics and systems thinking as well as the dilemma about hard and soft methodology are discussed from the general point of view. It is shown that the main problem in the modelling of complex systems derives from the complexity of the systems themselves and not from the shortcomings of the particular methodology. The role of the subject in the modelling of a complex system is discussed. The article continues with the Enterprise Simulation Model described with Forester's system dynamics for business behaviour and event oriented model for technology process. The methodology is sufficiently abstract to allow a qualitative and quantitative analysis of the system functioning through feedback loops. The multiple criteria function used at the evaluation of different scenarios was defined with the aid of a decision group using the group support system. The methodology was successfully tested for the reengineering process in a medium size factory.

Acknowledgement

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