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# DECISION MAKING: A COMPUTER-SCIENCE AND INFORMATION-TECHNOLOGY VIEWPOINT

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## ABSTRACT

We address the phenomenon of decision making from the viewpoint of computer science and information technology. The basic question from this viewpoint is: what can the computer offer to decision makers and how it can support their work? Therefore, the main issue is to provide support to people who make complex decisions. In this article, we first present the taxonomy of disciplines that are concerned with methodological and operational aspects of decision support. At the main level, we distinguish between decision sciences, which are concerned with human decision making, and decision systems, which address computer decision making. This is followed by basic definitions related to decision processes and their components. We also describe properties that characterise different classes of decision problems. In the main part of the article, we present three prevailing approaches to decision support and give illustrative examples of their application: decision analysis, operational research, and decision support systems. Finally, we make a short overview of the area of decision systems and its achievements.

## KEY WORDS

decision making, decision sciences, decision support, decision analysis, decision systems

## CLASSIFICATION

ACM: D.2.2, H.4.2, K.4.3, I.6

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## INTRODUCTION

Computers are everywhere: they are placed on tables in our offices and homes, they are installed in cars, washing machines and other equipment, we carry them around, and we even send them to other planets. With computers, we calculate, process data, solve problems, communicate with each other, and create art. When designing computer programs and applications, one of the key questions is the question of functionality: what can the computer offer to the users and how can it support their work? When dealing with decision-making problems and tasks, the question is therefore how can computers and information technology support people who are faced with difficult decisions, so that they can decide better, faster and more effectively. This is addressed in the area of decision support programs, systems, methods and techniques [1-3].

In decision support, we must answer many important questions. What exactly is decision making, how is it performed by people and how should we support it? Can we classify decisions and decision processes? Which of them can be effectively supported by information technology? Which are the main components of decision making? What are the input data and what are the expected output data of computerised processes? What exactly constitutes a "good decision"? In this article we present some answers to these questions from the viewpoint of disciplines, which are concerned with methodological and operational aspects of decision support. First, we present the taxonomy of these disciplines, give some basic definitions, and describe properties that characterize different classes of decision problems. In the main part, we present three prevailing approaches to decision support: decision analysis, operational research, and decision support systems. Finally, we make an overview of the area of decision systems.

## BASIC DISCIPLINES

When talking about decision making, a computer scientist usually starts with the question: who or what is making decisions, the man or the computer? In decision support, we wish to help people who make decisions; therefore we are primarily interested in *human decision making*. However, in computer science and related disciplines, such as artificial intelligence, the aim is also to make "intelligent" systems, i.e., computer programs and machines, which are able to make autonomous decisions by themselves. That is, the focus there is on *machine decision making*. As a consequence, we classify disciplines which are concerned with decision making into two main groups (Figure 1): *decision sciences* and *decision systems*, which are concerned with human and machine decision making, respectively.

*Decision sciences* refer to a broad interdisciplinary field interested in all aspects of human decision making. It draws on economics, forecasting, statistical decision theory, and cognitive psychology, and is typically divided into three main groups (Figure 1):

1. The first group is concerned with *rational decision making*. The approach is referred to as *normative* or *prescriptive*, where the decision problem is defined in terms of identifying the best (or optimal) decision, assuming an ideal decision maker who is fully informed, able to compute with perfect accuracy, and fully rational. Methods developed in this area are mainly theoretical; typical examples include decision theory, multi-attribute utility theory and game theory [4].
2. The second group is interested in how people really do make decisions. It has been clearly shown that people are rational only to some extent; they tend to use rules of thumb and take shortcuts to choose among alternatives. Often these shortcuts do well, but often they

lead to systematic biases and serious errors [5]. This approach is called *descriptive* and is typical for the research in *cognitive sciences*.

3. The third group is concerned with *decision support*: given what we know about rational decision making and actual behaviour, how can we help people to improve their decision making? This is the main area of interest for computer scientists and information technologists, who try to provide effective methods and tools for supporting human decision makers.

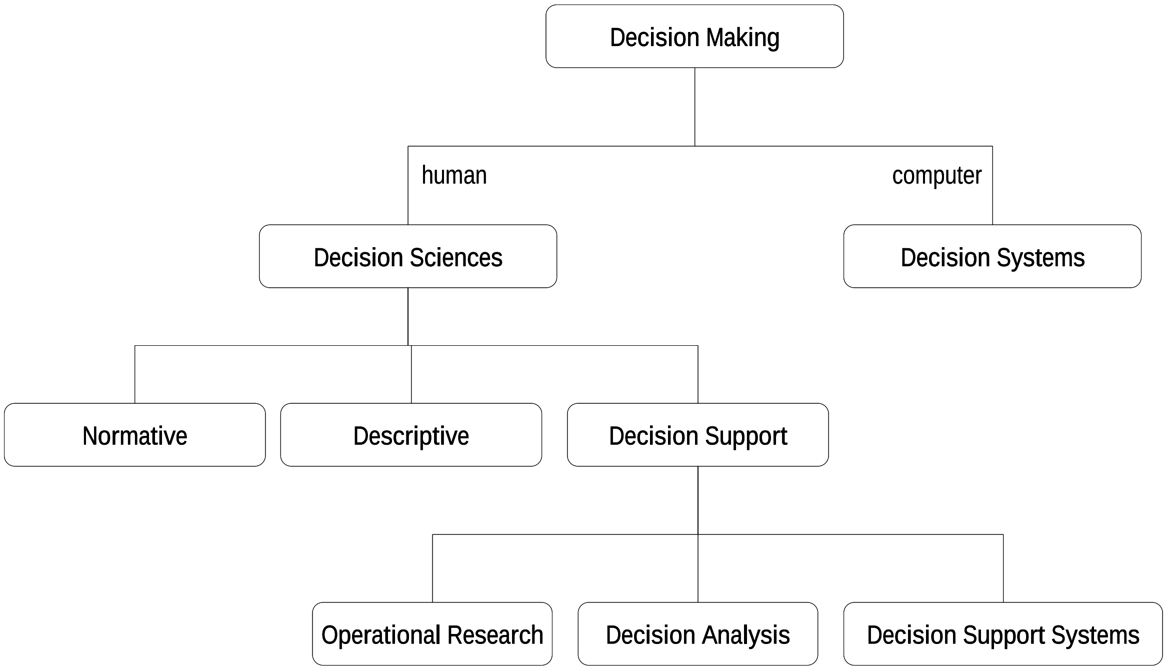


**Figure 1.** Disciplines addressing methodological and operational aspects of decision making.

In this article, we focus on the three decision support disciplines (Figure 1): operational research, decision analysis and decision support systems. However, before presenting them, we first give some basic definitions related to decision making and describe different types of decision problems.

## DECISION MAKING

*Decision making* is usually defined as a mental process, which involves judging multiple options or alternatives, in order to select one, so as to best fulfil the aims or goals of the decision maker [1, 4, 6]. Therefore, there are two main components involved in decision making: the set of *alternatives*, judged by the decision maker, and the *goals* to be satisfied with the choice of one alternative. The output of this process can be an action or an opinion of choice.

Decision making is a *process*. This means that in general it takes some time and effort until the choice is made, involving several activities, such as [6, 7]:

- identification of the decision problem;
- collecting and verifying relevant information;
- identifying decision alternatives;
- anticipating the consequences of decisions;
- making the decision;

- informing concerned people and public of the decision and rationale;
- implementing the selected alternative;
- evaluating the consequences of the decision.

The key step of this process is making the *decision* itself, that is, choosing the most preferred alternative using judgement based on available information. With the decision, we give precedence to the selected alternative, assuming (and hoping) that this alternative will provide the best (i.e., the easiest, most efficient, cheapest, safest, etc.) solution to our decision problem. The decision is considered a conscious and deliberate act, what makes the decision maker responsible for its consequences. The *implementation* of the decision often consumes resources, such as time, energy, money and willpower, and is therefore *irrevocable* [6]. The consequences of a decision cannot be taken back; if necessary, they can only be affected by new decisions.

## CLASSIFICATION OF DECISION PROBLEMS

Decision problems are incredibly diverse. On the one hand, we are faced with everyday problems, which are usually simple and easy to solve: when to get up in the morning, what kind of bread to buy, whether to stop at the red light or not, etc. On the other hand, there are difficult problems which require large resources, affect many people and have important consequences: which strategy to take on European market, how to organise public transportation in a capital city, etc. Somewhere in between are important problems of individuals (what to study?), families (where to live?) and organisations (how to survive in the economic crisis?).

In decision support, we are typically interested only in “sufficiently difficult” decision problems, which are “worth” approaching in an organised and systematic manner and which have sufficiently “important” consequences. In other words, it should make sense to collect information about these problems, think and discuss about the possible solutions, and in general support the process with some method, computer program or information system. It is also important to understand that it is possible to effectively support only decision problems and processes that are sufficiently well understood. When approaching a problem, we have to know what exactly we are deciding about, what are the goals and what are the possible consequences of the decision, we should at least partly know the alternatives and their properties, we have to be aware of possible uncertainties, etc.

Decision problems can be classified along different dimensions [4, 6-8]. One classification is into *routine* and *non-routine* problems, which often implies a considerable difference in *difficulty*. Routine decisions are taken frequently and repeatedly. The decision maker typically knows them well and feels familiar with the problem. All key factors, consequences and uncertainties are well understood and under control. Such decisions are usually easy. In contrary, non-routine decisions tend to be more difficult, particularly because of the lack of knowledge and experience in taking such decisions. Often, non-routine decisions are risky and have important consequences.

With respect to *frequency*, decision can be *one-time* or *recurring*. Although there is some overlap with the previous classification, the frequency dimension is important because it largely determines the focus of the decision-making process. With *one-time* decisions, the emphasis is on the decision itself: the goal is to find and implement the best alternative. The process ends when the alternative has been chosen (or implemented in some cases). From decision-support perspective, this usually requires the use of methods for the evaluation and analysis of alternatives, and the use of general-purpose decision support software. With *recurring* decisions, the focus usually shifts to finding the most effective method or procedure for choosing alternatives. Although it is still important to find the best alternative each time, it is often more important to implement an effective decision-making process. From decision-support perspective, this often requires to design and implement dedicated decision support software.

Another classification considers the *number of criteria*, which are taken into account when assessing alternatives. *Single-criterion* (or *single-attribute*) methods take into account only one criterion, most often some monetary value, such as profit or income. Many well-known decision analysis tools, such as decision tables and decision trees in their basic forms, consider only one criterion. However, most real-life decisions depend on *multiple criteria*; for example, in addition to return of investment (a single criterion), we may also want to consider the increase of market share and employment generated by the investment. The corresponding decision analysis methods are called *multi-criteria* or *multi-attribute*.

*Uncertainty* refers to a state of limited knowledge or information so that something is unknown or is not perfectly known [6]. *Uncertainty* occurs whenever there are external factors that influence the decision, but are beyond the control of the decision maker and are unknown to the decision maker at the time of decision. With respect to *uncertainty*, decision problems are classified in decision theory into [4; p.34]:

- *Decisions under certainty*: Here, the decision maker has all the necessary information about alternatives and the consequences of decisions are certain and accurate.
- *Decisions with risk*: The decision maker does not know the true value of external factors ("state of nature") for certain, but he can quantify his uncertainty through a probability distribution of possible outcomes.
- *Decision under strict uncertainty*: The decision maker feels that he can say nothing at all about the true "state of nature". In particular, he cannot quantify his uncertainty in any way.

Depending on the number and role of participants in the decision-making process, we distinguish between *individual* and *group* decisions. *Individual* decision problems typically involve a single decision maker. Alternatively, they can even involve more participants, provided that they have the same goals and decide "as one". In *group* decision-making processes, there are several individuals or groups that have different and often conflicting goals. In the latter case, decision support aims at resolving the conflict and finding the common solution, either by consensus or leverage.

For decision support in organisations, there is a very important categorisation of decision problems based on the *nature* of the decision to be made and the *scope* of the decision itself [8]. The *nature* of decision is represented with three categories referring to the level of *structure* of decision problems (Figure 2):

- *Structured decisions*: These are all decisions for which a well-defined decision-making procedure exists. This means that all inputs, outputs and internal procedures are known and can be specified. Structured decisions can be left to a clerk or a computer.
- *Semi-structured decisions*: Here, the decision has some structured elements but cannot be completely structured. We do not know how to specify at least one of the components (inputs, outputs, internal procedures). Computers can provide a great deal of specific help. Most organisational decisions are of this type.
- *Unstructured decisions*: Here, all decision components are unstructured. This may be because the decision is so new, so complex or so rare that we have not studied them completely. Computers can still help the decision maker, but only indirectly and with a low level of support.

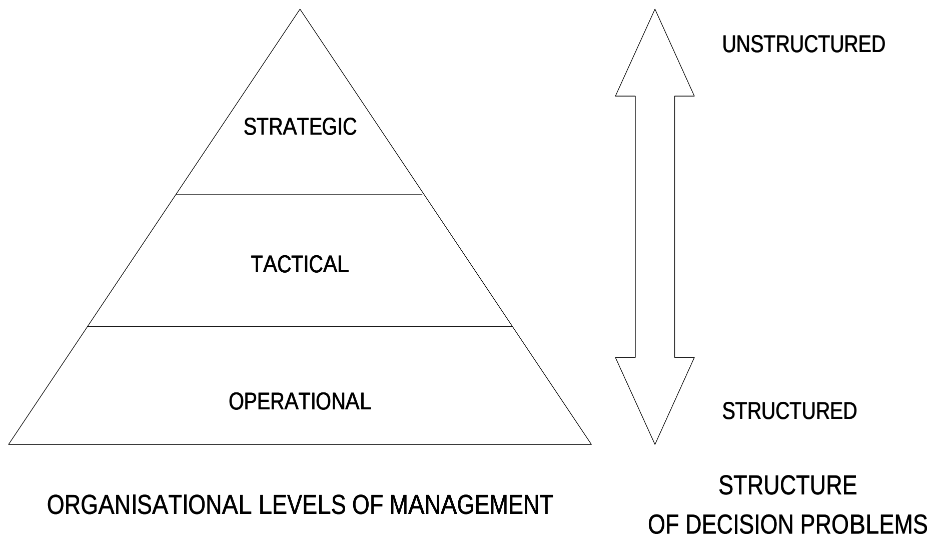


**Figure 2.** Classification of decision problems by scope (left) and nature (right).

Another dimension, *scope*, refers to the levels of management in an organisation (Figure 2):

- *Strategic decisions* affect the entire organisation, or a major part of it, for a long period of time. In most cases, they are made at the upper level of organisational management. Examples of strategic decisions are decisions about introducing a new product or service, entering a new market, or reorganising the production.
- *Tactical decisions* affect a part of the organisation for a limited time into the future. Tactical decisions are generally made by middle managers and take place in the context of previous strategic decisions. Typical examples are related, for instance, to personnel management: recruiting new employees and making expert teams.
- *Operational decisions* affects only current activities in an organisation; they have no or very limited impact for a short period of time. Operational decisions are usually made by lower level managers or non-managerial personnel. They are generally structured or semi-structured. Examples of operational decisions are whether to approve a loan to a client, or how to repair a malfunctioned machine.

The scope of decisions importantly affects the *characteristics of information* required in the process (Table 1). The understanding of information characteristics is an important factor for a successful design and implementation of any decision support system.

**Table 1**. Information characteristics by decision scope [8].

| *Information characteristic* | *Operational decisions* | *Strategic decisions* |
|---|---|---|
| **Accuracy** | High | Low |
| **Level of detail** | Detailed | Aggregate |
| **Time horizon** | Present | Future |
| **Frequency of use** | Frequent | Infrequent |
| **Sources** | Internal | External |
| **Scope** | Narrow | Wide |
| **Nature of information** | Quantitative | Qualitative |

Finally, let us mention *single-* and *multi-stage* decisions. In a *single-stage* decision process, there is only one key decision to be made. In contrast, a *multi-stage* decision processes consist of several related decisions, which can be taken *sequentially* or in *parallel*. Actually, the distinction between sequential and parallel decisions is sometimes difficult, because any decision process, even a single-stage one, consists of a series of other decisions. For example, when we encounter a decision process, we have first to "decide" how to approach it: intuitively, impulsively, ad-hoc, or in some organised way. We also have to "decide" which alternatives to take on board and which goals to consider. Who are the decision makers and with whom to collaborate? Where to get the relevant information? Which decision support method or computer program to use? And finally, after we have chosen the alternative, we have to "decide" for action. Essentially, this takes place as a decomposition of the decision process into a series of smaller and smaller decision subprocesses. We seek for a sequence of decision subproblems that are sufficiently easy to solve and can be combined together in order to solve the overall decision problem.

## DECISION SUPPORT METHODS

In this section we present three typical approaches to decision support and illustrate them through examples: decision analysis, operational research, and decision support systems.

### DECISION ANALYSIS

*Decision analysis* is popularly known as "applied decision theory" [6-7]. It is the discipline comprising the philosophy, theory, methodology, and professional practice necessary to address important decisions in an organised and formal manner. Decision analysis approaches a decision problem systematically by structuring and breaking it down into smaller and possibly more manageable subproblems. In doing that, it explicitly considers the possible decision alternatives, available information, uncertainties involved, and relevant preferences of the decision maker. It also attempts to formally represent these components and combine them in a form of decision models, which are used to assess, evaluate and analyse alternatives. In principle, rational decisions are proposed in this way. In the case of missing information and other difficulties, decision analysis tries to provide decisions which are not optimal but "satisfactory" or "sufficiently good".

Usually, the decision analysis process proceeds in stages, such as:

1. identification of the decision problem
2. identification of alternatives
3. problem decomposition and modelling
4. evaluation and analysis of alternatives
5. selection of the best alternative
6. implementation of the decision

If necessary, the stages can be intermixed or repeated. The most distinctive stages of decision analysis are the third stage, in which a *decision model* is developed, and the fourth stage, in which the model is used to *evaluate* and *analyse* alternatives. Usually, the model is developed by the decision maker using one of the many decision modelling methods or tools. If necessary, the decision maker can consult experts, who provide information and experience about the decision problem, and/or decision analysts, who give methodological advice and may even coordinate the whole process. Typical decision modelling techniques include decision trees, influence diagrams, and multi-attribute models [7].

Let us illustrate decision analysis concepts through a hypothetical decision problem. John is an economist who has just finished his MBA studies. He got four job offers from four companies, called A (a manufacturing company), B (banking), C (consulting), and D (information technology). John wants to take into account four important factors: *location*, *salary*, relation to *management science* (which he particularly likes), and *long term prospects* of the job. He wants to formalize these factors and use them to assess each job offer.

One of the most elementary decision analysis techniques is based on *pairwise comparison* of alternatives. Here, we do not actually consider any properties of alternatives, but only specify which alternative we like more than other. Given any two alternatives, A and B, there are three possible cases: we like A more than B (we write $A \succ B$), we like B more than A ($A \prec B$), or we equally like A and B (A~B). In theory [4], '$\prec$' and '~' are called *preference relations*; '$\prec$' is a *strict preference* relation, and '~' is an *indifference* relation.

Preference relations are conveniently represented in a *comparison matrix* (Table 2). In order to avoid comparing each alternative with itself, and to compare each pair of alternatives only once, more than half of the table is greyed-out and should be left empty. In the remaining cells, we enter 1, 0, or –1. The number 1 indicates that we prefer the alternative written in the first column over the alternative in the first row. The number –1 also indicates the strict preference, but in the reverse order. The number 0 indicates indifference.

**Table 2**. Comparison matrix of job offers.

| Alternative | A | B | C | D |
|---|---|---|---|---|
| **A** | | –1 | 1 | 0 |
| **B** | | | 1 | 1 |
| **C** | | | | –1 |
| **D** | | | | |

John's comparison matrix (Table 2) indicates the following preference relations: $A \prec B$, $A \succ C$, A~D, $B \succ C$, $B \succ D$, $C \prec D$. With some reordering and taking into account the principle of transitivity (if $X \succ Y$ and $Y \succ Z$, then $X \succ Z$), we get the overall ranking of alternatives: $B \succ A \sim D \succ C$. Therefore, B is the best job offer, which is followed by equally good A and D, and C is the worst of all. We get the same order if we add up the numbers in each row: B gets 2 "points", A and D 0, and C gets –1. Let us remark that John's table is consistent (logically correct), however it is generally possible to define the table inconsistently. Consider, for instance, entering the value –1 instead of 1 into the (B,C) cell. Fortunately, there are methods and software programs that can detect such inconsistencies.

The next possible step is to look at job offers in more detail and consider their positive and negative aspects. Table 3 illustrates a simple qualitative comparison method called *pros and cons analysis* [9]. In the table, good things ("pros") and bad things ("cons") are identified about each alternative. Lists of the pros and cons are compared one to another for each alternative. The alternative with the strongest pros and weakest cons is preferred. Pros and cons analysis is subjective and is usually suitable for simple decisions with few alternatives (2 to 4). It requires no mathematical skills and can be used without computers.

**Table 3**. Pros and cons analysis of job offers.

| Alternative | A | B | C | D |
|---|---|---|---|---|
| **Pros** | • relatively good salary | • very good salary<br>• interesting work<br>• good public image | • nearby location<br>• safe position<br>• clear promotion criteria | • easy and frequent promotions<br>• two friends are working there<br>• dynamic work |
| **Cons** | • work is not too interesting | • unfamiliar work<br>• long drive to location | • not too interesting<br>• low initial salary | • location is far<br>• small company<br>• unsafe position<br>• low initial salary |

Actually, pros and cons analysis takes an important step towards *multi-criteria* (or *multi-attribute*) methods. Table 3 contains words that describe some common properties of alternatives which are interesting for John: salary, location, promotion, safety, the presence of friends, etc. When assessing job offers, John confronts each of these alternatives' properties with his personal preferences and expectations. He tries to assess whether and to which extent the actual properties of job offers fulfil his objectives. *Multi-criteria methods* [10-11] aim to formalise these aspects of decision making. They require a definition of variables (parameters, attributes) that describe relevant properties of alternatives. Usually, variables are weighted in order to indicate that they are of different relative importance. Each alternative is assessed through the values of these variables. A final evaluation of alternatives is obtained by some aggregation procedure, for instance, a weighted sum.

Table 4 illustrates these concepts using the Kepner-Tregoe method [9, 12]. Kepner-Tregoe is a simple and commonly used multi-criteria method in which the attributes are assessed using the values from 0 to 10, where 0 indicates a very bad, and 10 a very good (ideal) value of the corresponding attribute. The same scale is used for weights: 10 indicates the most important attribute, and 0 an attribute of no importance for the decision. Alternatives are evaluated using the weighted sum, i.e., the sum of weights multiplied by attribute values.

The evaluation in Table 4 shows that the job offer B got the score of 244 and is the best. It is followed by C (228), A (204) and D (189). In the table, we can also look at individual properties of alternatives and assess their contribution to the final score. For instance, C obtained very high scores with respect to location, safety and promotion, but a low score with respect to the interestingness of the job.

An important aspect of multi-attribute models is that they can be used for various analyses of alternatives. In John's case, for example, he may feel that he has overestimated the importance of salary, but underestimated the importance of interestingness and promotion. Also, he may be uncertain about the promotions in company C. He can easily assess the effects of such changes by simply changing the corresponding values in the model and observing the new evaluations. For instance, he can take Table 4 and change the values as shown in Table 5 (the changed values are underlined). The result is that C has been degraded: it is still at the second place, but is now very close to A and D, whose order has changed. In any way, the decision is stable as B has remained firmly at the first place.

From here on, there are many ways to proceed towards more advanced decision analysis methods. For instance, when the number of relevant attributes grows and exceeds 10 or 15, we may want to use *hierarchical multi-criteria methods*, in which we structure attributes into a tree or a hierarchy. A typical representative of hierarchical methods is AHP, Analytical Hierarchy Process [13]. Figure 3 illustrates a possible way to organise John's job-offer assessment attributes into a tree.

**Table 4**. Multi-criteria evaluation of job offers using Kepner-Tregoe method.

| Weight | Attribute \ Alternative | A | B | C | D |
|---:|---|---:|---:|---:|---:|
| 10 | **Salary** | 8 | 10 | 6 | 5 |
| 7 | **Interestingness** | 4 | 8 | 2 | 6 |
| 5 | **Location** | 4 | 2 | 9 | 1 |
| 5 | **Safety** | 4 | 6 | 9 | 2 |
| 4 | **Image** | 8 | 9 | 7 | 7 |
| 3 | **Promotion** | 6 | 4 | 8 | 10 |
| 3 | **Co-workers** | 2 | 0 | 4 | 8 |
| | **Evaluation** | **204** | **244** | **228** | **189** |

**Table 5**. What-if analysis of job offers. Changed values are underlined.

| Weight | Attribute \ Alternative | A | B | C | D |
|---|---|---|---|---|---|
| 8 | **Salary** | 8 | 10 | 6 | 5 |
| 10 | **Interestingness** | 4 | 8 | 2 | 6 |
| 5 | **Location** | 4 | 2 | 9 | 1 |
| 5 | **Safety** | 4 | 6 | 9 | 2 |
| 4 | **Image** | 8 | 9 | 7 | 7 |
| 5 | **Promotion** | 6 | 4 | 4 | 10 |
| 3 | **Co-workers** | 2 | 0 | 4 | 8 |
| | **Evaluation** | **212** | **256** | **218** | **217** |

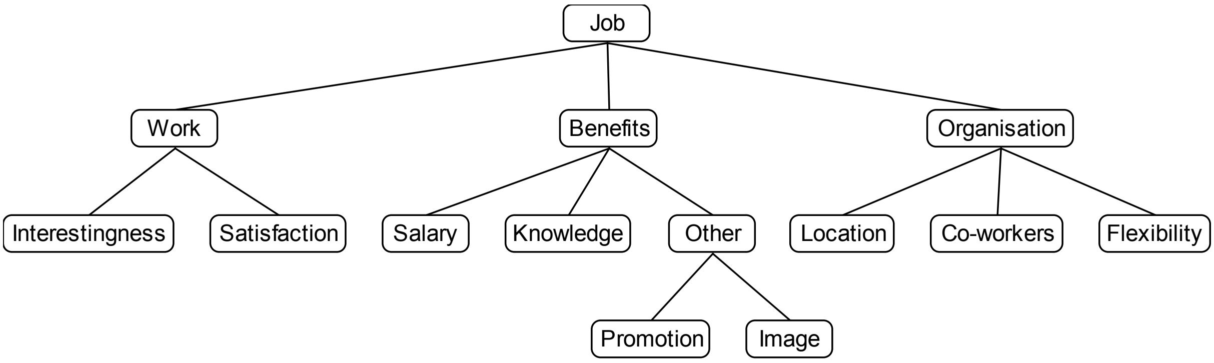


**Figure 3.** Hierarchical structure of criteria for the assessment of job offers.

When developing multi-criteria models, we often need methods that acquire attribute weights from the decision maker: examples of such methods are AHP, SMART and SWING [9]. Instead of the weighted sum, we may use more advanced value functions and aggregation methods [14]. Numeric attributes and quantitative assessment can be replaced or complemented with symbolic attributes and qualitative assessment, for example using the method DEX [15]. Uncertainty aspects and multi-stage decisions can be addressed through decision trees [16] or influence diagrams [7].

All these methods are supported by many computer programs. These can be of general or specific purpose. Typical *general purpose* programs are spreadsheets and mathematical toolboxes, in which the users can either define their own methods and procedures for decision analysis, or can use already implemented templates or dedicated plug-in software components. Examples include the programs Microsoft Excel, OpenOffice.org, MATLAB, Mathematica and R, and the plug-ins TreePlan in PrecisionTree.

*Specific-purpose programs* in general provide the following functionality: (1) acquisition, formulation and modification of a decision model and its components, (2) acquisition and representation of data about alternatives, (3) evaluation and analysis of alternatives, and (4) presentation of results through reports. Specific-purpose programs for decision tree modelling are, for example, TreeAge Pro and DPL. Influence diagrams can be developed with Analytica and GeNIe. There are many programs for quantitative multi-criteria modelling: HiView, Decision Pad, Logical Decisions, Prime Decisions, ELECTRE, Expert Choice, Criterium Decision Plus, HIPRE, V.I.S.A, Winpre, Web-HIPRE. Qualitative multi-attribute modelling is supported by programs such as DEXi and DoctuS. Further information about the mentioned computer programs is available through the WWW page *IJS Decision Support Resources* [17].

## OPERATIONAL RESEARCH

The aim of *operational research* (or *operations research*) [18-19] is similar to decision analysis: the application of analytical methods and mathematical models for decision support. However, the emphasis in operational research is on *mathematical modelling* and finding *optimal* solutions of mathematically defined problems – rather than assessing given alternatives and finding "sufficiently good" ones, as in decision analysis. Typical applications of operational research are characterized largely by the need to allocate limited resources, such as time, energy and money. Such problems often occur in government, business, engineering, economics, and the natural and social sciences.

The contribution from operational research stems primarily from:

- structuring the real-life situation into a mathematical model, abstracting the essential elements, so that a solution relevant to the decision maker's objectives can be sought,
- exploring the structure of such solutions and developing systematic procedures for obtaining them,
- developing a solution, including the mathematical theory if necessary, that yields an optimal value of the system measure of desirability.

Typical operational research techniques include linear and nonlinear programming, network optimization models, combinatorial optimization, multi-objective decision making, and Markov analysis.

To illustrate the approach of operational research, let us show an application of *linear optimisation* for John's next decision problem. Namely, John has taken the job offer at the bank (alternative B above). Now, his work must be properly organised. According to his skills, John can perform the following tasks:

C: work with clients,
D: data and document maintenance,
E: education, attending courses and seminars.

C is most profitable for the bank and is worth 4 monetary units per hour. The value of D is 1, whereas the value of E is only 0.1. According to internal rules, John must spend per month at least 10 hours working on C, and at least 20 hours on E. However, John is a beginner and must be therefore supervised. Full supervision is necessary when working on C, but only one hour per day (1 out of 8) of supervision is necessary for D. E requires no supervision. The total number of working hours per month is 180, however the supervisor can spend with John at most 30 hours per month. The question is: how to organise John's work so that it will be most profitable for the bank?

The problem is formulated mathematically. Let $x_c$, $x_d$ and $x_e$ denote the number of John's working hours per month for each task. Using this notation, we can define the constraints:

| | | | |
|---|---|---|---|
| $x_c + x_d + x_e$ | $\leq$ | 180 | the maximal number of John's working hours per month is 180; |
| $x_c + 1/8\ x_d$ | $\leq$ | 30 | the supervisor's work with John is limited at 30 hours; he fully supervises the task C, but only every eighth hour of D; |
| $x_c$ | $\geq$ | 10 | John must work with clients at least 10 hours per month; |
| $x_d$ | $\geq$ | 0 | John's time spent in the office must not be negative; |
| $x_e$ | $\geq$ | 20 | John must study at least 20 hours per month. |

The total value of John's monthly work is

$$V = 4x_c + x_d + 0.1x_e$$

We wish to maximise this value.

In this way, we formulated the problem in terms of a *linear program*. There are efficient methods for solving linear programs, which are implemented in most general purpose computer programs mentioned above. In John's case, the optimal solution is:

$x_c$ = 11.43 h/month
$x_d$ = 148.57 h/month
$x_e$ = 20.00 h/month

With this solution, the value of $V$ is maximal and equals to 196.29 monetary units.

## DECISION SUPPORT SYSTEMS

*Decision support systems* (DSS) are defined as interactive computer-based information systems intended to help decision makers utilize data and models in order to identify and solve problems, and make decisions [1, 3, 8]. In contrast with decision analysis and operational research, where the emphasis is on making and using decision models, DSS focus on providing information technology for decision makers at various levels in organisations. The emphasis is on providing relevant information and presenting it in a suitable form so as to improve the decision making process and tasks.

The main characteristics of DSS are:

- DSS incorporate both data and models,
- they are designed to assist managers in their decision processes in semi-structured or unstructured decision-making tasks,
- they support, rather than replace, managerial judgment,
- their objective is to improve the quality and effectiveness (rather than efficiency) of decision making.

DSS can support decision makers in a number of different ways. They can store data and provide means to search for relevant data items. More advanced techniques include query languages and data warehouses. Data can be viewed and analysed using pivot tables and other methods of on-line analytical processing (OLAP). DSS can provide computational and statistical models, for instance for trend analysis. With data mining algorithms, the decision maker can find interesting patterns in data. The results can be presented in reports and tables, as well as graphically using advanced visualisation techniques. DSS can incorporate all types of decision analysis and operational research models presented above. Consequently, using these models, DSS can evaluate and assess decision alternatives or find optimal solutions of mathematically formulated problems. DSS can integrate data from different sources and of different types (relational data, documents, video, etc.). Also, DSS can contain rules that guide specific decision processes. Last but not least, DSS can provide communication and other means to support the collaboration of decision makers.

Taking into account all this variety and using the mode of assistance as the criterion, DSS are differentiated into the following types [1]:

- *communication-driven DSS*: support more than one person working on a shared task,
- *data-driven DSS* or *data-oriented DSS*: emphasize access to and manipulation of a time series of internal company data and, sometimes, external data,
- *document-driven DSS*: manage, retrieve, and manipulate unstructured information in a variety of electronic formats,

- *knowledge-driven DSS*: provide specialized problem-solving expertise stored as facts, rules, procedures, or in similar structures,
- *model-driven DSS*: emphasize access to and manipulation of a statistical, financial, evaluation, optimization, or simulation model.

## DECISION SYSTEMS

For the final section, let us step from human to computer decision making – that is, from decision sciences to *decision systems* (see Figure 1). Computer decision making is fundamentally different from human decision making and has an advantage that we understand it very well. Computers make decisions according to programmed procedures, which can be easily analysed, modified and observed during their operation. Although we cannot really compare the mechanisms of human and computer decision making, we can still observe and compare the performance of the two.

The computer has to be *programmed* to carry out some given task. This means that the programmer has to define a sequence of instructions that are executed by the computer. When executing instructions (i.e., when the program is running), it is often necessary that the program reacts differently in different situations. On the basis of data, which is available to the program, it must "decide" which sequence of instructions to take for further execution. For this reason, one of the fundamental characteristics of computer programs is their ability to *branch*: programs contain instructions that "switch" between branches composed of other sequential instructions. All instructions are (in principle) pre-defined by the programmer, however the branching occurs while the program is running, depending on the current state of the program and data available to the program. In this way, the program dynamically chooses between different courses of actions. Externally, this appears as an ability of the computer to adapt and make decisions.

For example, let us consider a very simple mathematical operation: division of two numbers, say $x/y$. This operation makes sense only if $y \neq 0$. Therefore, even in this very simple case, the computer must "decide" whether to carry out the division or not. Before each division, the computer must check the value of $y$. If $y=0$, it should not make the calculation, but rather issue some message to the user or perform some other corrective action. Otherwise, the division is possible and the program should calculate the result. In a computer programming language, these instructions may be formulated as follows:

```
read(X,Y)
if Y=0 then
    write('Error: division by 0')
else
    R := X/Y
    write(X, ' divided by ', Y, ' is equal to ',R)
```

Every computer program contains instructions like these. Even though instructions are explicitly specified by the programmer and their execution is deterministic (fully predictable), we can gradually add more and more instructions and combine them into complex branching sequences. In this way, we can create computer programs that exhibit very complex behaviour, even to the point that is often referred to as "intelligent": intelligent control systems, intelligent agents, game playing programs, etc. For example, chess-playing programs are already capable of outperforming most human players, including the world chess champion [20].

Among "intelligent" computer programs, there is a particularly interesting class of programs which are able to "learn". These programs either observe their own performance or monitor some data generated through performance of other systems. Based on examples of successful or unsuccessful performances, machine learning programs can find patterns that explain the reasons for such behaviour, they can find rules that improve performance, or can even modify themselves (by modifying their own operating instructions) to achieve better performance in the future. The scientific discipline that is concerned with the design and development of algorithms that allow computers to change behaviour based on data is called *machine learning* [21-22].

Autonomous vehicles provide good examples of advanced decision systems. In order to explore the surface of Mars, two Mars Rover vehicles [23] were sent by the USA to that planet. The distance between Earth and Mars is so large that it takes 12 minutes in average for a signal to travel that distance. This makes it almost impossible to steer the vehicle from Earth. Therefore, Mars Rovers were designed as highly autonomous vehicles, which were receiving basic commands from the Earth, but were also capable to navigate challenging and unknown terrain, investigate targets, and detect scientific events [24].

Another example, which is currently at the borderline of decision systems, is related to the *DARPA Urban Challenge* [25], a prize competition held in 2007. The requirements were to build a fully autonomous vehicle, which must be entirely autonomous, using only the information it detects with its sensors and public signals such as GPS, and which would be able to drive autonomously between two given points in an urban area, obeying the driving laws. The main event took place on November 3, 2007, on a course in California, which involved a 96 km urban area course, to be completed in less than 6 hours. Six of 11 vehicles accomplished the mission, what is considered a groundbreaking success.

## REFERENCES


[1] Power, D.J.: *Decision Support Systems: Concepts and Resources for Managers*.
Quorum Books, Westport, 2002,

[2] Bohanec, M.: *Decision Support*.
In Mladenić, D.; Lavrač, N.; Bohanec, M. and Moyle, S., eds.: *Data Mining and Decision Support: Integration and Collaboration*. Kluwer Academic Publishers, Boston, pp.23-53, 2003,

[3] Turban, E.; Aronson, J. and Liang, T.-P.: *Decision Support Systems and Intelligent Systems*.
Prentice Hall, Upper Saddle River, 7th Edition, 2005,

[4] French, S.: *Decision Theory: An Introduction to the Mathematics of Rationality*.
Ellis Horwood Halsted Press, New York, 1986,

[5] Ariely, D.: *Predictably Irrational*.
HarperCollins Publishers, New York, 2008,

[6] Skinner, D.C.: *Introduction to Decision Analysis.*
Probabilistic Publishing, Gainesville, 3rd Edition, 2009,

[7] Clemen, R.T.: *Making Hard Decisions: An Introduction to Decision Analysis*.
Duxbury Press, Pacific Grove, 1996,

[8] Mallach, E.G.: *Decision Support and Data Warehouse Systems*.
Irwin, Burr Ridge, 2000,

[9] Baker, D. et al.: *Guidebook to Decision-Making Methods.*
USA Department of Energy, WSRC-IM-2002-00002, 2002,
http://emi-web.inel.gov/Nissmg/Guidebook_2002.pdf,

[10] Keeney, R.L. and Raiffa, H.: *Decisions with Multiple Objectives: Preferences and Value Tradeofs*.
Cambridge University Press, 1993,

[11] Bouyssou, D.; Marchant, T.; Pirlot, M.; Tsoukiàs, A. and Vincke, P.: *Evaluation and Decision Models with Multiple Criteria: Stepping Stones for the Analyst.*
International Series in Operations Research and Management Science **86**, Springer, Boston, 2006,
[12] Kepner, C.H. and Tregoe, B.B.: *The New Rational Manager*.
Princeton Research Press, Princeton, 1981,
[13] Saaty, T.L.: *Multicriteria Decision Making: The Analytic Hierarchy Process*.
RWS Publications, 1993,
[14] Grabisch, M.; Marichal, J.L.; Mesiar, R. and Pap, E.: *Aggregation Functions*.
Cambridge University Press, 2009,
[15] Bohanec, M. and Rajkovič, V.: *DEX: An Expert System Shell for Decision Support*.
Sistemica **1**(1), 145-157, 1990,
http://kt.ijs.si/MarkoBohanec/pub/Sistemica90.pdf,
[16] Hammond, J.S.; Keeney, R.L. and Raiffa, H.: *Smart Choices: A Practical Guide to Making Better Decisions.*
Harvard Business School Press, 1999,
[17] Bohanec, M.: *IJS Decision Support Resources*.
http://kt.ijs.si/MarkoBohanec/dss.html,
[18] Hillier, F. S. and Lieberman, G. J.: *Introduction to Operations Research*.
McGraw Hill, New York, 8th Edition, 2005,
[19] Taha, H.A.: *Operations Research: An Introduction*.
Prentice Hall, Upper Saddle River, 8th Edition, 2006,
[20] Feng-Hsiung, H.: *Behind Deep Blue: Building the Computer that Defeated the World Chess Champion*.
Princeton University Press, 2002,
[21] Mitchell, T.: *Machine Learning*.
McGraw Hill, 1997,
[22] Marsland, S.: *Machine Learning: An Algorithmic Perspective*.
Chapman & Hall/Crc, 2009,
[23] – : *Mars Exploration Rover Mission*.
California Institute of Technology, Jet Propulsion Laboratory,
http://marsrover.nasa.gov/home/index.html,
[24] Bajracharya, M.; Maimone, M.W. and Helmick, D.: *Autonomy for Mars Rovers: Past, Present, and Future*.
IEEE Xplore **41**(12), 44-50, 2008,
[25] – : DARPA *Urban Challenge*.
http://www.darpa.mil/grandchallenge/index.asp.

# ODLUČIVANJE: STAJALIŠTE RAČUNALNIH ZNANOSTI I INFORMACIJSKE TEHNOLOGIJE

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## SAŽETAK

Razmatramo pojavu odlučivanja sa stajališta računalne znanosti i informacijske tehnologije. Osnovna pitanja tog stajališta su: što računalo može ponuditi donosiocima odluka i kako ono može poduprijeti njihov rad? Pritom, glavni je slučaj davanja podrške ljudima koji donose kompleksne odluke. U ovom radu, prvo je predočena taksonomija disciplina u kojima se koriste metodološki i provedbeni vidovi podrške odlučivanju. Na temeljnoj razini razlikujemo znanost o odlučivanju i sustave odlučivanja. Znanost o odlučivanju tiče se ljudskog odlučivanja, a sustavi odlučivanja računalnog odlučivanja. Na navedeno se nastavljaju definicije vezane uz procese odlučivanja i njihove komponente. U radu su također opisana svojstva koja karakteriziraju različite klase problema odlučivanja. U glavnom dijelu članka navedeni su najzastupljeniji pristupi podršci odlučivanja i popraćeni ilustrativnim primjerima njihove primjene: analizom odlučivanja, operacijskim istraživanjima i sustavima podrške odlučivanju. Na kraju je dan kraći prikaz područja primjene sustava odlučivanja i njihovih dostignuća.

## KLJUČNE RIJEČI

odlučivanje, znanost o odlučivanju, podrška odlučivanju, analiza odlučivanja, sustavi odlučivanja