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Original article

The application of logical decision trees to the decision-making process in ill-structured problems

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ABSTRACT

Decision-making is a process which has accompanied the human being since time immemorial and in various areas of their activity. It should result in making a choice that meets the expectations (conditions) of the decision maker to the greatest extent. Decisions can be made on the basis of information which is not always complete and reliable. Sometimes it may happen that it is incomplete and reliable or complete but unreliable. Then, it concerns ill-structured problems. The purpose of this article is to verify whether ill-structured problems can be solved/supported in a way based on an operating algorithm. In the article, a case study with complete but unreliable information as well as with complete and reliable information was used. Logical decision trees were employed in the study. The result of the study allowed for, among others, establishing that the analysis of an ill-structured problem using logical decision trees consists in performing steps which follow one another in a logical sequence creating thus a sequence of operations, and therefore an operating algorithm, which confirms that solving ill-structured problems can be supported/implemented using an algorithm.

KEYWORDS

decision-making, ill-structured decisions, logical decision trees

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Introduction

Decision-making is a process which has accompanied the human being since time immemorial and in various areas of their activity. It should result in making a choice that meets the expectations (conditions) of the decision maker to the greatest extent. Current knowledge in the field of decision-making combines scientific achievements from various disciplines, e.g., mathematics, statistics, economics, psychology, management, game theory, computer science, philosophy, sociology, or political science [1, p. 18]. A decision can be made on the basis of quantitative and qualitative data. In both cases, the information may be reliable and complete (well-structured problems) or entirely to the contrary, i.e., incomplete and unreliable (ill-structured problems). Note that there are also ill-structured problems where the available information (in whole or in part) is unreliable but complete or by analogy incomplete and reliable. In the literature, one can find the statement that "In the case of well-structured problems, all elements of the decision-making process can create an algorithm, conditioned by a logical order of conduct. Unstructured problems require creative thinking and solving them cannot be subordinated to algorithms" [2, p. 240]. However, it must not be forgotten that there are also ill-structured problems. The purpose of this article is to verify whether ill-structured problems can be solved/supported in a way based on an operating algorithm. Considering the foregoing, the research problem took the form of an answer to the question: Could ill-structured problems be solved/supported by means of an algorithm?

1. Decision-making process, problems associated with it and types of problems with regard to their structuring

The term "decision" derives from the Latin word *decision*, which is equivalent to "ruling, determination or resolution". A decision constitutes a conscious and non-random (deliberate) choice of one option from many available ones [3, p. 110]. Making decisions involves choosing one solution from amongst other acceptable and unacceptable options. This process is based on logically interconnected mental operations, executed in a structured and proper order, which allows for assessing a decision situation and selecting the most advantageous variant. The hotspot arousing the need to start the decision-making process is the emergence of a problem [3, p. 113]. A problem, according to the authors of the article, is the difference between what we consider reality and its state, which we wish to perceive. Solving the problem should bring the decision-maker as close as possible or even owing to it they should achieve what they assumed as their objective.

In the literature, there are many studies of the stages in the decision-making process, both those based on an operating algorithm (prescriptive) and those providing description and explanation (descriptive). Various normative models of decision-making and its stages are presented in the table below (Table 1).

Only some of the decision-making models and their stages are presented in Table 1. Regardless of how this subject is approached, all stages within a given model represent a structured and logical sequence of operations, with the ultimate goal of choosing the best solution. When making a decision, the decision maker bases their choice on information from the

Table 1. Normative decision-making models and stages

Decision-making model	Stages of the decision-making process
by Valenzi, Altman and Hodgetts (monocriteria) [2, p. 42]	1. Problem discovery. 2. Specific problem identification. 3. Establishing the criterion for assessing decision-making variants. 4. Developing a list of alternative solutions. 5. Assignment of the implementation effects of each proposed option. 6. Selecting the most suitable solution. 7. Implementation of the selected variant.

Decision-making model	Stages of the decision-making process
by Robbins and Coulter (multicriteria) [2, p. 44]	1. Problem identification. 2. Specifying the decision criteria. 3. Weighting the criteria. 4. Developing alternatives. 5. Analyzing alternatives. 6. Selecting an alternative. 7. Implementation of the selected alternative. 8. Evaluation of the decision effectiveness. The usefulness of the alternative is the key feature and the decision is made on this basis.
by Sutherland [2, p. 46]	1. Emergence of the need to make a decision (the goal). 2. Gathering a priori information. 3. Gathering a posteriori information as a result of empirical research. 4. Developing a model. 5. Defining possible solutions. 6. Defining evaluation criteria. 7. Evaluation of variants. 8. Distinguishing the best variant. 9. Decision. 10. Implementation of the selected variant into practice. 11. Model adjustment resulting from feedback. The variant characterized by the greatest usefulness is implemented.
by Holt [2, p. 47]	Stages of the decision-making process: 1. Diagnosing the problem. 2. Analyzing the environment. 3. Identifying the problem. 4. Developing alternatives. 5. Evaluating solutions. 6. Distinguishing the best alternative. 7. Implementing the selected alternative in practice. 8. Evaluation of decision effectiveness.
Operational research [4, p. 117]	Stages of the decision-making process: 1. Developing a model. 2. Solving the model and obtaining the optimal decision. 3. Verification of the model and its potential adjustment. 4. Control – the decision is corrected based on the feedback received.
Fuzzy decision-making rules [4, p. 124; 5, p. 1]	The decision-making model is based on two values: 1 (true) and 0 (false). However, it should be assumed that the assignment of these values is not unchangeable or defined in an unambiguous way. Between these two states, there is a continuum of intermediate values, and the boundaries between them are not clearly established (e.g., "mostly true" or "approximately true", "the value of approx. 4").

Source: The authors' own study based on [2, p. 244-245].

past and present, while the implementation of the decision taken concerns the future [2, p. 242]. In psychology, the decision-making process is commonly divided into three phases:

1. Pre-decision phase – defining the problem and gathering information about the available options.
2. Decision phase – making a decision.
3. Post-decision Phase – conducting evaluation of the decision which has been made [6, p. 68].

However, it is worth mentioning the proposal presented by J. Adair, who introduced a classic approach (Fig. 1) [7, p. 23], which will be used to determine if the analysis of the problem, using logical decision trees, matches the overall framework of the decision-making process.

In order to formulate a decision-making problem, one should possess the information on:

– the decision-maker: Who is it? (machine, group of people, person),
– limiting conditions that define a set of admissible (implementable) decisions,
– decision selection criteria.

The criteria utilized in the decision-making process can be either of qualitative or quantitative character. The values of the applied decision criteria can be compared with the characteristics of the decision or with thresholds, as well as compared with one another with reference to individual decision alternatives [8, p. 5-6].

Decisions can be made intuitively, meaning they are made without relying on specific tools and procedures. Intuitive decision-making involves using information about relationships between objects and facts without analyzing the underlying causes or seeking a comprehensive understanding of them. In contrast, the rational decision-making style requires decision-makers to thoroughly evaluate different alternative scenarios and probabilities for each option before making a decision. Additionally, it involves critical evaluation of evidence and adhering to a structured process which requires both time and conscious effort. Rational procedures are helpful in establishing decision criteria, identifying multiple alternatives, and evaluating them objectively. Unlike the intuitive decision-making style, the rational decision-making style involves careful and methodical consideration of all possible decision choices. The analysis

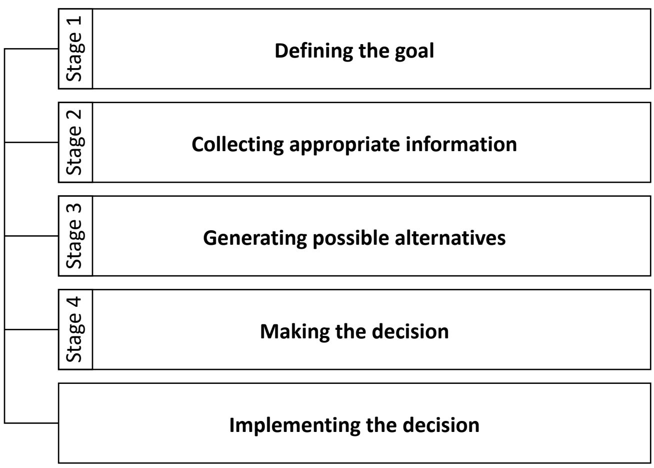

Fig. 1. The classical approach to decision-making
Source: [7, p. 23].

of the possibilities using the rational decision-making style requires the decision-maker to deliberately evaluate them and determine the expected consequences [9, p. 106-107].

During the decision-making process, obstacles may arise from both the cognitive limitations of the decision-maker and the complexities inherent in the decision-making environment. Cognitive limitations may be the result of insufficient knowledge of the decision-making problem (or lack thereof), excessive aspirations of the decision maker and insufficient time to make a decision. On the other hand, the level of uncertainty in the decision-making environment can be influenced by factors such as the number of available decision options, the quantity of accessible information [1, p. 46], and its quality (completeness and accuracy). In order to mitigate potential issues that may arise during the decision-making process, it is advisable to:

- be thoroughly prepared to deal with the problem,
- approach problem-solving without unnecessary emotions,
- allocate (to the best extent possible) an appropriate amount of time for making the decision,
- conduct a comprehensive analysis of the problem.

However, there is not always the right amount of time to make a decision, access to substantive knowledge, emotional distance to the problem, analytical skills, and even more impact on access to the right amount and quality of information on the problem under study [1]. These are the reasons for introducing a division of problems, understood as initiators of decision-making processes: well-structured, ill-structured, and unstructured [10, p. 274].

Well-structured problems can be effectively represented in numerical form and can be solved using mathematical models. From a logical standpoint, it is evident that well-structured problems may also involve qualitative variables. However, in both well-structured and ill-structured problems, the available information must be comprehensive and reliable. Examples of such problems are: inventory planning, production planning, results analysis. On the other hand, unstructured problems do not have explicitly defined quantitative dependencies between elements. For this reason, they can only be presented in a qualitative way, in the form of verbal description. The dependencies between criteria cannot be measured at all, and the available data is often incomplete and characterized by uncertainty. Examples of such decisions include creating strategies within a company or implementing innovation [2, p. 240]. According to the authors of the article, it is worth emphasizing that everyday life is full of inaccurate and approximate concepts. This state of affairs may result from, among others, not having enough time to observe the phenomenon, machine system, or in-depth analysis of the case. Therefore, often due to the lack of time, the decision-maker must contend themselves with approximate values or often with "indifferent" decisions (answer "I don't know") in the case of certain configurations of theoretical events [11, p. 141]. Imprecise concepts and approximate concepts arise when information is both complete and uncertain or certain but incomplete. Such problems can be described as ill-structured.

2. Analyzing an ill-structured problem and structural optimization of its solutions as support for decision-making

The aim of this article is to analyze a problem of a qualitative nature, which contains dependable and complete information as well as complete but uncertain information, in order to check whether ill-structured problems (with uncertain information) can be solved/supported by an algorithm. It is worth mentioning here that uncertain information is one in the case of which we do not know whether the logical function will take the value 0 or 1, and they are also referred to as neutral states ∅ [12, p. 114]. Logical decision trees were chosen as the method that will enable this verification.

In general, there are many approaches to the problem of knowledge representation (i.e., an organized set of information items together with the rules of their interpretation [13, p. 25]) and various inference techniques (i.e., formulating conclusions) related to it, which are used to find the final solution to the problem [14, p. 82]. The language of mathematical logic can be regarded as one of knowledge representation patterns. There are two primary advantages of utilizing logic for problem solving/decision support:

1. The language of logic is very similar to the way people think about the world and express these thoughts in sentences of natural language. The categories that people use in their speech and thoughts include constructions such as: objects, relations (relationships between objects), statements of simple and complex facts, expressions of conditional facts, sentences or sentence conjunctions.
2. Logic offers precise methods intended for inference based on proving theorems. During their process of thinking, people utilize similar logical reasoning.

Logical decision trees are a logic-based method which utilizes the "Quine-McCluskey algorithm for minimizing individual multivalued logical functions". The above-mentioned trees are a graphical method that visualizes the structures of solutions to a practical problem, which are composed of paths marked on the branches of the tree according to the coded values of variables in a multi-valued way. The variables are stacked vertically, and true solutions (obtained after applying constraints) are marked as paths (bold branches) from the root to the tree vertices and together they constitute the sum of the logical function products. On the other hand, all branches (even those without bolding, in the form of paths) are a set of theoretical solutions. All branches and paths not marked in bold indicate a value of 0 for a given logical function. These branches and paths represent false solutions [15, p. 93].

Problems of qualitative nature often involve multiple criteria. However, the primary goal of using logical decision trees is to determine the most critical parameter (criterion) upon which the decision-making process depends to the greatest extent. This means that when making a decision, the parameter that turns out to be the most important should be taken into account first, because its values affect the decision to the greatest extent. Being guided by other parameters is not forbidden but remember that the hierarchy of importance decreases as you climb up the tree, so it is not advisable when you want to make the best decision. Hence, logical decision trees can be regarded as a valuable approach for optimizing the structure of problem solutions, with a specific emphasis on the hierarchical organization of structural and operational parameters or other variables. This significantly simplifies the decision-making process since there is no need to analyze the problem with reference to multiple factors, and attention can be directed towards the states assumed by the criterion closest to the root of the logical decision tree. Building a hierarchy of variables/parameters/criteria is possible due to the fact that in logical decision trees it is possible to swap tiers with decision variables (criteria), i.e., their ordering. Indeed, it is impossible to achieve the desired outcome using logical decision trees and the classical Quine-McCluskey method. However, logical decision trees are highly effective in optimizing machine systems, streamlining processes, and providing support in solving problems of qualitative nature. The scope of their application is wide-ranging, encompassing decision-making support in everyday life, businesses (problems from the area of organization and construction-exploitation), and even covering military matters.

2.1. Example of applying decision trees in an ill-structured problem

The problem analyzed was the qualitative problem of going for a walk or staying at home, for which the limiting conditions were determined by the person's experience. The above-mentioned decision may be influenced by many factors; however, 3 criteria were chosen for the purpose of presenting the method of logical decision trees: weather, free time, willingness.

Operating algorithm:

1. Determine the selection criteria/factors influencing the decision and their states, along with assigning multivalued value judgments to them (0.1.2…), as in Table 2. In the analyzed case, a binary value judgement is sufficient, as the variables/criteria only assume two states (0 and 1),

   Selection criteria: weather (x_1), free time (x_2), willingness (x_3).

Table 2. Code record of criteria and their states

	0	1
x_1	rain	sun
x_2	no	yes
x_3	no	yes

Source: The authors' own development.

2. Determination of limiting conditions.

   Limiting conditions:

   1. I will go for a walk, if the sun is shining, I have free time and feel like doing it (dependable information).
   2. I will go for a walk if it is raining, and I feel like doing it (dependable information).
   3. I will go for a walk if I do not have free time but want to (dependable information).
   4. I don't know whether I will go for a walk if it is raining, I have free time and I don't want to (uncertain information).

3. Creation of a morphological table with theoretical solutions (2*2*2=8) based on the criteria, their states and the limiting conditions.

Based on Table 3, 6 logical decision trees were constructed (3!=6). The number of trees is determined by the number of decision variables, according to the formula:

$$\text{Number of trees} = n!, \qquad (1)$$

where:

n – number of decision variables $x_1, x_2, \ldots, x_n$.

In the case of ill-structured problems with uncertain information, it is necessary to proceed in two ways [12, p. 114]:

1. In the analysis, we use solutions which are certainly true (decision-I'm going for a walk) as true solutions. In contrast, an uncertain decision is treated as a Boolean function for which the value is equal to 0.
2. In the analysis, both true (I'm going for a walk) and indifferent solutions ∅ (I don't know if I'm going for a walk) are considered as decisions for which the Boolean function takes the value of 1.

Table 3. Overview of theoretical solutions

No.	x_1	x_2	x_3	Decision
1	0	0	0	no
2	0	0	1	yes
3	0	1	0	I don't know
4	0	1	1	yes
5	1	0	0	no
6	1	0	1	yes
7	1	1	0	no
8	1	1	1	yes

Source: The authors' own development.

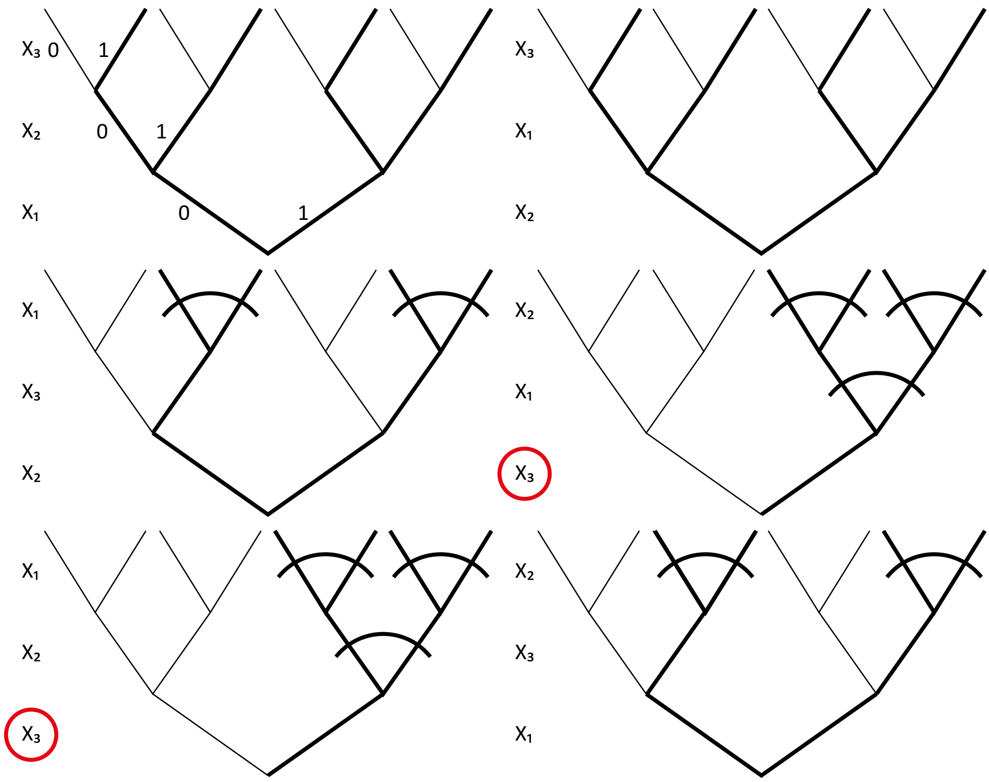

Fig. 2. Logical decision trees for all tier combinations with marked true solutions, where an uncertain decision is treated as a false one
Source: The author's own development.

The basis for the construction of logical decision trees (Fig. 2, Fig. 3) is the data for all theoretical solutions (Table 2). There can be only one variable/criterion (x_1, x_2, x_3) on each tier of the tree. Due to the possibility of cutting off full bundles (the process of minimizing the

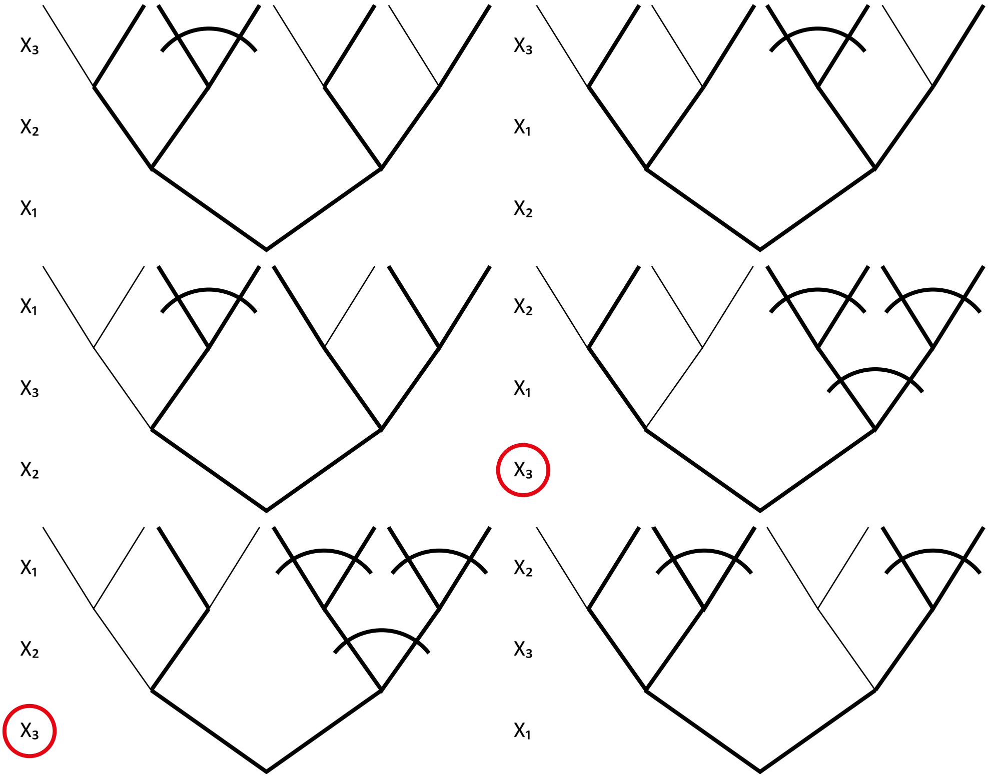

Fig. 3. Logical decision trees for all tier combinations with marked real solutions, where the uncertain decision is treated as a true one
Source: The author's own development.

logical function) going from top to bottom of the tree, it is possible to obtain true solutions, which are, sort of, the essence obtained from all true solutions, and thus contain the most important information regarding the optimality of making a decision. Speaking in the language of mathematical logic, it can be said that the minimization of a logical function is made possible by gluing operations.

Transformation is termed as a gluing operation [15, p. 36]:

$$Aj_o(x_r) + \ldots + Aj_{mr-1}(x_r) = A, \tag{2}$$

where:

r = 1, …, n and A – a partial elementary product, whose variables of individual literals belong to the set $\{x_1, \ldots, x_{r-1}, x_{r+1}, \ldots, x_n\}$.

On the other hand, the following transformation is called an incomplete gluing operation [15, p. 36-37]:

$$Aj_o(x_r) + \ldots + Aj_{mr-1}(x_r) = A + Aj_o(x_r) + \ldots + Aj_{mr-1}(x_r), \tag{3}$$

where:

r = 1, …, n and A – a partial elementary product, whose variables of individual literals belong to the set $\{x_1, \ldots, x_{r-1}, x_{r+1}, \ldots, x_n\}$.

The characters of the gluing operation record are entered separately in the columns, and the overall minimization process can be performed on logical decision trees.

Table 4 is a list of all combinations of decision variables with the corresponding number of true branches obtained by the true branch gluing process, where a given variable could assume two states (0 and 1) with a given combination of tree tiers.

3. Conclusions

3.1. Conclusions regarding the investigated case study

The analysis of the ill-structured problem of going for a walk or staying at home allowed the following statements:

1. The most important parameter in the analyzed problem of going for a walk is x_3, which is the willingness to go for a walk. This means that neither the weather nor having free time have such a significant influence on the decision and the decision-maker should be guided mainly by whether he or she feels like going for a walk.
2. It can be said that the importance of weather and having free time are equivalent both when the uncertain information is treated as a Boolean function, the value of which is equal to 0, and when it is considered to be true. Then it does not matter whether x_1 or x_2 is located on its own or the other variable's locations (in systems

Table 4. Combinations of decision variables with the number of true branches corresponding to them

Tree No.	Ordering of logical variables			Number of true branches
1. Uncertain decision treated as a Boolean function which assumes the value of 0				
1	x_1	x_2	x_3	10
2	x_2	x_1	x_3	10
3	x_1	x_3	x_2	4
4	x_2	x_3	x_1	4
5	x_3	x_1	x_2	1
6	x_3	x_2	x_1	1
2. An uncertain decision treated as a Boolean function which assumes the value of 1				
1	x_1	x_2	x_3	9
2	x_2	x_1	x_3	9
3	x_1	x_3	x_2	6
4	x_2	x_3	x_1	6
5	x_3	x_1	x_2	4
6	x_3	x_2	x_1	4

Source: The authors' own development.

where the place of the variable x_3 is the same and uncertain information is treated in the same way) in achieving the same number of true branches. To sum up, it can therefore be said that the importance of weather and having free time is equivalent in making the decision to go for a walk.

3.2. General conclusions

After the analysis of the indicated problem, it can be stated with all certainty that logical decision trees are a method that allows for solving ill-structured problems with uncertain and certain information based only on qualitative criteria. However, it should be noted that the method indicated also allows for the analysis of problems where quantitative data is available. Therefore, the trees discussed herein are a very universal method for decision-making support.

In addition, it can be stated that:

1. Conducting the analysis of a problem using logical decision trees involves steps which follow one another in a logical order. Thus, creating a sequence of actions, and therefore an operating algorithm [16].
2. The sequence of operations concerning the analysis of the problem using logical decision trees matches the general model of the decision-making process (without the decision implementation stage – Table 5). Logical decision trees do not themselves define a goal or collect relevant information, but they force the decision-maker to do perform these actions, because without this, analysis using this method is not possible.
3. The implementation of a clearly defined procedure results in the prioritization of the decision variables which influence the end result to be achieved the most. The decision remains with the decision maker in accordance with the results of the analysis and its implementation.

Table 5. The stages of problem analysis using logical decision trees in relation to the stages of the decision-making process

No.	Stages of the decision-making process	Analysis of the problem using logical decision trees
1	Defining the goal	Defining the problem/aim of the study necessary for the analysis.
2	Gathering relevant information	Determination of selection criteria/factors influencing the decision and their states with assignment of binary value judgements to them. Establishment of limiting conditions.
3	Generation of possible variants	Creation of their states and limiting conditions of the morphological table with theoretical solutions on the basis of the criteria. On this basis, one should build logical decision trees and apply gluing operations (cutting off full branches), leading to the tree(s) with the smallest number of true branches, in the root(s) of which the parameter is found on which the decision will depend to the greatest degree.
4	Decision-making	The decision should be made with particular reference to the parameter that has the greatest influence on the decision (found in the root of the tree with the minimum number of true branches).

Source: The authors' own development.

The above conclusions confirm the achievement of the research goal and a positive solution to the research problem, which is summarized by the statement that ill-structured problems can be solved/supported by an algorithm.

This article is an introduction to further considerations related to the optimization of more complex problems of an ill-structured nature. In the future, it is aimed to optimize one of the phases of the command process, which is planning.

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Conflict of interests

The authors of the article hereby submit a declaration affirming the absence of conflict of interest.

Author contributions

Paweł Kałuża and Milena Sadowińska-Kałuża have contributed to the research, interpretation of the results and writing the article. Paweł Kałuża read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

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Biographical note

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Zastosowanie logicznych drzew decyzyjnych do procesu podejmowania decyzji w problemach słabo ustrukturalizowanych

STRESZCZENIE Podejmowanie decyzji stanowi proces, który towarzyszy człowiekowi od zawsze i w różnych obszarach jego działalności. Jego rezultatem powinno być dokonanie wyboru, który w największym stopniu spełnia oczekiwania (warunki) decydenta. Decyzje można podejmować na podstawie informacji, które nie zawsze są pełne i pewne. Czasem może się zdarzyć, że są niepełne i pewne lub pełne, ale niepewne. Wówczas dotyczą one problemów słabo ustrukturalizowanych. Celem niniejszego artykułu jest weryfikacja, czy problemy słabo ustrukturalizowane można rozwiązywać/wspierać ich rozwiązywanie w sposób oparty na algorytmie działań. W artykule wykorzystano analizę przypadku z informacjami pełnymi, ale niepewnymi oraz pełnymi i pewnymi. Posłużono się w niej logicznymi drzewami decyzyjnymi. Jej wynik pozwolił m.in. na stwierdzenie, że analiza problemu słabo ustrukturalizowanego za pomocą logicznych drzew decyzyjnych polega na wykonaniu kroków, które następują po sobie w logicznej kolejności. Tworząc tym samym ciąg czynności, a zatem algorytm działania, co potwierdza, że rozwiązywanie problemów słabo ustrukturalizowanych może być wspierane/realizowane za pomocą algorytmu.

SŁOWA KLUCZOWE podejmowanie decyzji, decyzje słabo ustrukturalizowane, logiczne drzewa decyzyjne

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