Multi-Valued Dependency Analysis Methodology. A Novel Approach to Modeling Uncertainty in Data

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Abstract

This paper presents a novel approach to the analysis of data with uncertain information. The classic approach of bivariate logic does not allow for the modeling of intermediate states, which are particularly important when studying phenomena characterized by uncertain information. The proposed methodology, based on assumptions of Łukasiewicz's logic, introduces a transformation of logical values to the set $\{-1, 0, 1\}$, which allows for an intuitive interpretation of truth, falsity, and lack of information. An unusual aspect of the approach is the use of a contiguity matrix, determined from the implication operator, to assess the degree of dependence between variables. The method was applied in the analysis of real-world data. The results confirm its effectiveness and efficiency in analyzing dependencies while accounting for uncertainty due to missing or ambiguous data, with a linear time complexity.

Keywords: uncertainty modeling, incomplete data mining, multi-valued logic

1. Introduction

Observation of the world and the need for data processing influence the development of various fields, including logic. The most well-known is classical or Aristotelian logic. It operates on two values: truth (1) and falsehood (0). However Łukasiewicz noticed that between truth and falsehood, there are intermediate values, called *the possible* [17]. There are values for which truth status has not yet been determined, e.g. future random events. In Łukasiewicz's logic, the value of ½ does not denote a lack of knowledge, but an actual, gradual state of truth. It can be used to model uncertainty, intermediate states, or probabilistic logic.

The basis of the proposed data mining approach was the uncertainty on student entrepreneurship potential and the forms of support for economic activity expected by students. According to reports from institutions specializing in public opinion research and the analysis of social and political data, one of the most frequently occurring uncertainties — occurring on average in about 20% of cases — is the response *I don't know*. This response can indicate both a lack of knowledge on the part of the respondent and the absence of a subjective, evaluative opinion on the matter. On the other hand, responses missing completely at random are also frequently encountered in data, often resulting from respondents simply skipping questions without answering them for various reasons, such as reluctance to answer certain topics or lack of time [4].

In this paper, based on the assumptions of Łukasiewicz's three-valued logic, we model un-

certainty, situations that cannot be classified as true or false. The proposed methodology uses a transformation of logical values to the set $\{-1, 0, 1\}$, which allows an intuitive interpretation of truthfulness, falsity and lack of information. The main contributions of this paper are as follows:

- a novel approach to data analysis with a large amount of missing values;
- innovative concept of using an adjacency matrix to determine the degree of dependencies between variables;
- effective application of the methodology to analyze real-world data from a conditional branching questionnaire with multiple-response questions.

The paper is organized as follows: In Section 2, an introduction to the data mining approaches applied to uncertainty modeling is presented. The explanation of the novel method is provided in Section 3, while the data and experiments are described in Section 4. The methodological effectiveness is evaluated through external validation by comparing the results obtained with those reported in the literature, as detailed in Section 5.

2. Preliminaries

In this paper, we use the assumptions of Łukasiewicz's three-valued (Ł3) logic to model uncertainty. To provide a context, in the second column in Table 1, we first recall the fundamental operators in Łukasiewicz's logic (cf. [9]).

In our approach the values $\{-1, 0, 1\}$ are better suited to the intuitive meaning of truth (1), falsehood (-1), and information deficiency (0). The bijective function that transforms the structure (Ł3) into (Ł3') is $f(x) = 2x - 1$. This logic (Ł3') is isomorphic to the three-valued Łukasiewicz logic (Ł3), with the operators presented in Table 1.

Table 1. Logical operators in Łukasiewicz three-valued logic on two different sets of truth values

Operator	{0, 0.5, 1}	{-1, 0, 1}
Negation ($\neg x$)	$1 - x$	$-x$
Conjunction ($x \wedge y$)	$\min(x, y)$	$\min(x, y)$
Disjunction ($x \vee y$)	$\max(x, y)$	$\max(x, y)$
Implication ($x \to y$)	$\min(1, 1 + y - x)$	$\min(1 - x + y, 1)$

The logic table is presented in Table 2 (cf. [24]).

In our research, we use the fact that implication reflects the degree of dependence between an antecedent and a consequent.

3. Methodology of Multi-Valued Dependency Analysis

For clarity, algebraic notation is used. First, the questions that serve as premises are selected, followed by those that serve as decisions. It is worth noting that the same set of premises can be analyzed for different decisions. Therefore, in this paper, the decision vector is denoted as d^k, where k represents the index within the set of potential decision queries.

Consequently, the response value of the j-th predicted response for the i-th respondent is written as R_{ij} in the response matrix R while the decision response value for the i-th respondent is denoted as d_i^k. The sets of person and response indices are denoted as $M = \{1, \ldots, m\}$ and $N = \{1, \ldots, n\}$, respectively.

Table 2. Truth table for Łukasiewicz's three-valued logic (Ł3')

x	y	$\neg x$	$x \vee y$	$x \wedge y$	$x \rightarrow y$
1	1	-1	1	1	1
1	0	-1	1	0	0
1	-1	-1	1	-1	-1
0	1	0	1	0	1
0	0	0	0	0	1
0	-1	0	0	-1	0
-1	1	1	1	-1	1
-1	0	1	0	-1	1
-1	-1	1	-1	-1	1

In order to demonstrate the developed methodology, a fragment of the collected data was used. In the presented example in (1) the matrix R is considered, which contains values of $|N| = 7$ answers for $|M| = 13$ persons. The columns of the matrix R (denoted as r^j) contain the responses to exemplary survey questions Q_1 to Q_7, while the decision vector d^k corresponds to Q_8:

$$R = \begin{bmatrix} 1 & -1 & 1 & -1 & 1 & 1 & -1 \\ -1 & -1 & 0 & -1 & -1 & -1 & -1 \\ -1 & -1 & 1 & 1 & 1 & -1 & 1 \\ -1 & -1 & 1 & -1 & -1 & -1 & -1 \\ -1 & 1 & -1 & -1 & -1 & -1 & -1 \\ 0 & -1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 0 & -1 & -1 & -1 & -1 & -1 \\ -1 & -1 & -1 & 1 & 0 & -1 & -1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 0 \\ -1 & 1 & 1 & 1 & 1 & -1 & -1 \\ -1 & -1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & 1 \\ -1 & 0 & -1 & -1 & -1 & 1 & -1 \end{bmatrix}, d^k = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 1 \\ -1 \\ -1 \\ -1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ -1 \end{bmatrix}. \quad (1)$$

Next, the $IMP(R, d)$ matrix is defined, indicating whether a relationship exists between the response to the $j-th$ question and the decision of the $i-th$ respondent. Specifically, we introduce:

$$IMP(R, d^k)_{ij} = a_{ij} \rightarrow d_i^k \text{ for } i \in M \text{ and } j \in N. \quad (2)$$

This research is based on a survey, the degree of trust in relation to the studied group must be taken into account. To examine whether relationships exist between the questions considered as predicates and the decisions, the number of implications that were true for the entire group of respondents was calculated. Thus, the degree of dependency vector $dv(R, d^k)$ is defined as follows:

$$dv(R, d^k)_j = \frac{\sum_{i=1}^{n} x_{ik}}{|N|}, \text{ where } x_{ij} = \begin{cases} 1, & if\ IMP_{ij} = 1 \\ 0, & otherwise \end{cases}, i \in M, j \in N, \quad (3)$$

where $|N|$ is the number of respondents.

$$IMP(R,d^k)=\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & -1 & 1 & 1 & 1 & 1 & 1\\ 0 & 1 & 1 & 1 & 1 & 1 & 1\\ -1 & 0 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1 & 1 & 1 & 1\\ 1 & 0 & 1 & 1 & 1 & -1 & 1 \end{bmatrix}, dv(R,d^k)\approx \begin{bmatrix} 0.85\\ 0.77\\ 1.00\\ 1.00\\ 1.00\\ 0.92\\ 1.00 \end{bmatrix}^T. \tag{4}$$

Assuming that a relationship exists between the $j-th$ and $k-th$ questions r^j and d^k with $\epsilon \geq 0$ accuracy, then the adjacency matrix A is defined as follows:

$$a_{ik}=\begin{cases} 1, & dv(r^j,d^k)+\epsilon \geq 1\\ 0, & othercase. \end{cases} \tag{5}$$

The adjacency matrix, adopted from graph theory [25], represents the relationship between premises and conclusions.

Based on (5) with $\epsilon = 0.08$, the adjacency matrix $A(R,d^k)=\begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$ indicates degrees of dependencies between question Q_4 and question Q_7. Strong dependencies occur only between five out of the eight responses to question Q_4 and question Q_7, as presented in Fig. 1.

In our research, $\epsilon = 0$. Methodological validity, the research sample, and the response consistency verified by a subject matter expert indicated that the collected survey data is reliable and can be used to draw valid conclusions.

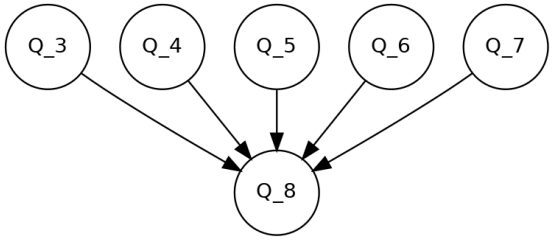

Fig. 1. The dependency graph for R and d^k

The proposed method is based on Zadeh's compositional inference rule [1], which employs a fuzzy IF–THEN structure. Due to the nature of the data, the fuzzy implication is replaced with the three-valued Łukasiewicz implication. As a result, the method can be extended to support rules of a more complex form:

- IF (Q_A AND Q_B) THEN Q_C,
- IF (Q_A OR Q_B) THEN Q_C,
- IF Q_A THEN (Q_C AND Q_D),
- IF Q_A THEN (Q_C OR Q_D),

where Q_A, Q_B, Q_C, and Q_D are linguistic fuzzy variables describing the respondent's answer to the question. This process requires constructing an extended matrix R' and an extended decision vector $d^{k'}$, whose columns may take one of the following forms:

$$r^{j_1} \wedge r^{j_2}, \quad r^{j_1} \vee r^{j_2}, \quad d^{k_1} \wedge d^{k_2}, \quad d^{k_1} \vee d^{k_2}.$$

4. Data and Experiments

The data used in the experiments comes from a representative study of a university support for student entrepreneurship, which was based on the original psychometric test conducted on a sample of 1,526 students. The research included students of all fields of study, full- and part-time, first- and second-cycle students, studying in their native language and English. A detailed description of the collected data and the methodology for its collection is available at [10].

It should be emphasized that the data was gathered using a conditional branching questionnaire. The branches are presented in Figure 2. Three-valued logic is used to model uncertainty and deal with situations that cannot be clearly classified as true or false. The values $\{-1, 0, 1\}$ indicate true, false, and no information, respectively. To determine the relationship between expectations regarding university support for student entrepreneurship and demographic metrics (characterizing students participating in the study, see Table 3), each branch was analyzed separately.

Table 3. Demographic metrics

Metric	Category	Abbr	Number of instances
Gender	Women	W	739
	Men	M	787
Study track	Polish language	P	1275
	English language	E	251
Degree level	Bachelor	BSc	1288
	Master	MSc	238

Here, due to restrictions, only for the external branch on the right side in Figure 2, the degrees of relationships between the reasons why master students do not use the support offered by the university when starting a business and the reasons why they do not plan to use it in the future are presented in Table 4.

Exclusively, only the strongest 100% relationships are analyzed. The determined relationships, based on the conditional branching questionnaire, are presented in Tables 5 – 7. The abbreviations of the metric category are used in the first columns in Tables 5 – 7. The conditional branching questionnaire used at the data collection stage had an adaptive structure that dynamically changed the path of questions based on a respondent's answers. Some of the questions were binary (Yes, No). These questions were marked as Y and N in the tables according to the given answer.

The validation of the developed methodology was conducted by a domain expert, a specialist in the field of entrepreneurship. The purpose of the validation was to assess the accuracy, relevance, and usefulness of the results in the context of expectations regarding university support for student entrepreneurship.

5. Assessment of Methodological Effectiveness

It is worth emphasizing that the data comes from a representative study examining university support for student entrepreneurship. This is actual collected data, not simulated. Methodolog-

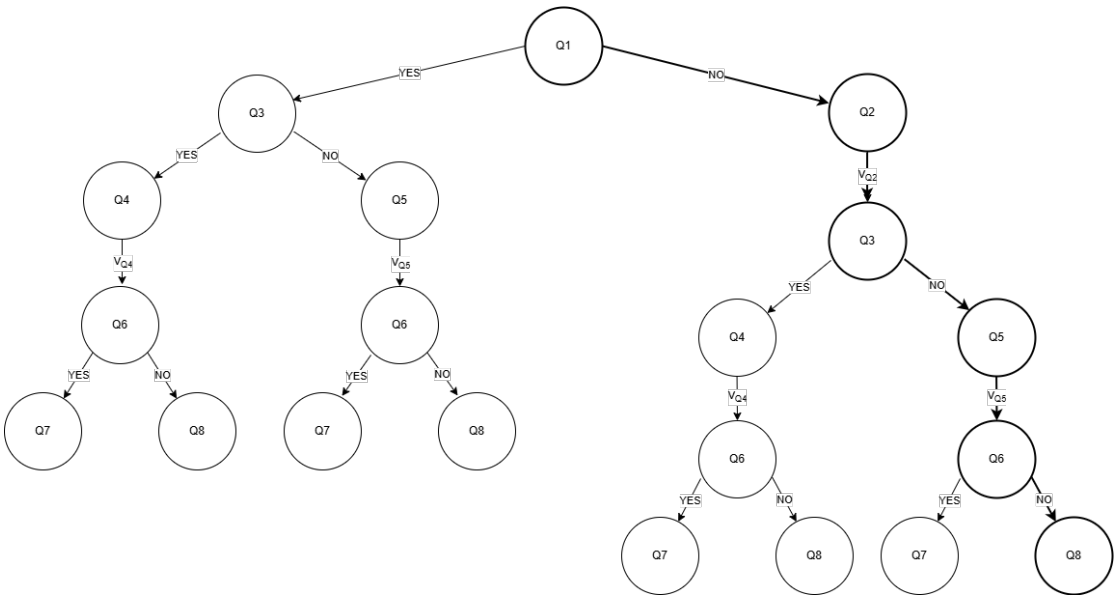

Fig. 2. Characteristics of the conditional branching questionnaire

Table 4. Degrees of the relationship between the reasons why master's students do not use the support offered by the university when starting a business and the causes why they do not plan to use it in the future. The external branch on the right side in Figure 2

	Q8_1	Q8_2	Q8_3	Q8_4	Q8_5	Q8_6	Q8_7	Q8_8
Q5_1	0.46154	0.30769	0.30769	0.46154	0.38462	0.23077	0.23077	0.15385
Q5_2	0.69231	0.69231	0.69231	0.76923	0.76923	0.61538	0.61538	0.61538
Q5_3	**1.00000**	**1.00000**	**1.00000**	**1.00000**	**1.00000**	**1.00000**	**1.00000**	**1.00000**
Q5_4	0.76923	0.76923	0.61538	0.76923	0.76923	0.69231	0.61538	0.61538
Q5_5	0.84615	0.92308	0.84615	0.92308	0.92308	0.92308	0.84615	0.84615
Q5_6	0.92308	**1.00000**	0.92308	**1.00000**	0.92308	**1.00000**	0.92308	0.92308

ical effectiveness was evaluated through external validation by comparing the results obtained with those reported in the literature. A similar approach was used, among others, by Fagiolo et al. [7] in the context of a developed taxonomy of agent-based models in economics, as well as by Mathiassen & Wold in 2021 [18], who compared results obtained through the imputation of survey data with those reported in the literature. The adopted research method consisted of several stages. First, relevant literature sources related to the studied topic were identified. Then, a comparative analysis was conducted. For this purpose, the results obtained using the new methodology were juxtaposed with those found in the literature. Finally, the research process concluded with an interpretation of the findings obtained through the developed methodology in relation to the results provided by the literature review.

Table 5 presents the perspective of individuals running a business (Q1_1) who used UITM's support in setting it up (Q3_1) and are interested in receiving support for new businesses in the future (Q6_1). Men used all forms of UITM's support (Q4) and want to continue using them, mainly in the areas of financing and legal advice (cf. [22]). Women were less likely to use support that included financial advice and assistance in creating business models. In the future, they mainly expect help with developing a business plan (Q7). The results contribute to the discussion on gender differences in entrepreneurship [2] and the perception of barriers

Table 5. The strongest relationships identified in the conditional branching questionnaire $[Q1, Q3, Q4, Q6] \Rightarrow Q7$ in Figure 2

	Q1	Q3	Q6		Q7_1	Q7_2	Q7_3	Q7_4	Q7_5	Q7_6	Q7_7	Q7_8	Q7_9	Q7_10
E	Y	Y	Y	Q4_2	1	1								
E	Y	Y	Y	Q4_3		1								
E	Y	Y	Y	Q4_4		1								
E	Y	Y	Y	Q4_5		1								
E	Y	Y	Y	Q4_6		1								
E	Y	Y	Y	Q4_7	1	1	1						1	
P	Y	Y	Y	Q4_4		1								
P	Y	Y	Y	Q4_7	1	1	1	1						1
BSc	Y	Y	Y	Q4_4		1								
BSc	Y	Y	Y	Q4_7	1	1	1							
W	Y	Y	Y	Q4_1	1									
W	Y	Y	Y	Q4_3		1								
W	Y	Y	Y	Q4_4	1	1								
W	Y	Y	Y	Q4_5	1	1								
W	Y	Y	Y	Q4_7	1	1	1							
M	Y	Y	Y	Q4_1		1		1	1		1	1		
M	Y	Y	Y	Q4_2	1	1	1	1	1	1	1	1	1	1
M	Y	Y	Y	Q4_3	1		1		1	1		1		1
M	Y	Y	Y	Q4_4		1		1	1		1	1		
M	Y	Y	Y	Q4_5					1			1		
M	Y	Y	Y	Q4_6					1			1		
M	Y	Y	Y	Q4_7	1	1	1	1	1	1	1	1	1	1

Table 6. The strongest relationships identified in the conditional branching questionnaire $[Q1, Q3, Q5, Q6] \Rightarrow Q7$ in Figure 2

	Q1	Q3	Q6		Q7_1	Q7_2	Q7_3	Q7_4	Q7_5	Q7_6	Q7_7	Q7_8	Q7_9	Q7_10
BSc	Y	N	Y	Q5_3									1	
E	Y	N	Y	Q5_3				1					1	
E	Y	N	Y	Q5_5				1		1			1	
W	Y	N	Y	Q5_5		1								
MSc	Y	N	Y	Q5_3	1	1	1	1	1	1	1	1	1	1
MSc	Y	N	Y	Q5_5	1	1								
MSc	Y	N	Y	Q5_6			1							
M	Y	N	Y	Q5_5						1			1	
E	N	N	Y	Q5_5			1							
E	N	N	Y	Q5_6		1								
MSc	N	N	Y	Q5_5			1							
MSc	N	N	Y	Q5_6	1									
W	N	N	Y	Q5_6	1									

to entrepreneurial initiatives [21]. Polish-speaking students focused on marketing assistance and thematic training (Q4) but plan to extend the scope of support to include financial and legal aspects (Q7). English-speaking students are more flexible in their business plans [14], and used a wider range of support services, including financial advice, assistance in creating business models, and obtaining financing (Q4). First-cycle students are more likely to need administrative and legal assistance when setting up businesses (Q4) and are more interested in university support (Q6)[28].

In turn, Table 6 presents the opinions of people running businesses (Q1_1) who have not used UITM's support (Q3_2) but are interested in it for new ventures (Q6_1), as well as the opinions of students without businesses (Q1_2) who have not had contact with the UITM's support offer (Q3_2) but are interested in it in the context of planned businesses (Q6_1). Among people running businesses, first-cycle students who have not used UITM's support considered

Table 7. The strongest relationships identified in the conditional branching questionnaire $[Q1, Q3, Q5, Q6] \Rightarrow Q8$ in Figure 2

	Q1	Q3	Q6		Q8_1	Q8_2	Q8_3	Q8_4	Q8_5	Q8_6	Q8_7	Q8_8
E	N	N	N	Q5_6	1							
MSc	N	N	N	Q5_5				1				
E	Y	N	N	Q5_3	1	1	1	1	1	1	1	1
E	Y	N	N	Q5_4	1							
E	Y	N	N	Q5_5			1	1				
E	Y	N	N	Q5_6		1	1					
BSc	Y	N	N	Q5_5				1				
MSc	Y	N	N	Q5_3	1	1	1	1	1	1	1	1
MSc	Y	N	N	Q5_6		1		1		1		
W	Y	N	N	Q5_3								1
W	Y	N	N	Q5_5				1				
W	Y	N	N	Q5_6		1		1				
MSc	Y	N	N	Q5_3	1							

the market offer to be better (Q5) (in line with the position of Karaś [12] and Lu et al. [16] regarding the inadequacy of university support to students' expectations), but for a new business, they would be interested in UITM's help mainly in obtaining funds (Q7). Second-cycle students, despite their reservations towards university support, over time see its value and plan to use the entire range of available support (from business plans to legal and financial advice) (Q7). This could be an effect of the advantage of easy access to various forms of support at university (cf. [29], [23]), even with their limitations, over professional but more expensive support from market institutions. Women prefer accounting advice, while men support in business models and raising funds (Q7). The results support the view that representatives of both genders differ in their motivations for entering business, which may affect the way they use available forms of support (cf. [13]; [19]). English-speaking students initially avoided support from UITM (Q3_2), but in the case of new companies, they declare interest in financial and business assistance (Q7). This perspective is consistent with Wang & Huang [27] and emphasizes the evolutionary nature of students' expectations regarding financial support from the university in the process of new firm formation. Among students without companies (Q1_2) who had no contact with UITM's business support offer and who are interested in it in the context of planned businesses (Q6_1), the language of studies, the level of education, and gender were of key importance. English-speaking students did not use the university's support due to the lack of financial support in the offer (Q5), but when planning a business, they are interested in accounting or legal advice (Q7). This finding supports the conclusions of the research by Choi et al. [3]. Second-cycle students plan to use support mainly in developing a business plan (Q7). This position is dominant among women and is consistent with the results of Czyżewska [6]. In the case of men, however, no relationship was found between the attributes studied.

Independently, Table 7 presents the views of students running a business (Q1_1) who have not used UITM's support (Q3_2) and are not interested in it in the future (Q6_2), as well as the position of people without companies (Q1_2) who have not had a contact with the UITM's support offer (Q3_2), and are not interested in it (Q6_2). The first group includes English-speaking students. They did not use UITM's support when setting up a business because their market offers better support (cf. [20]). Moreover they were afraid of obligations to the university (Q5) (a similar finding is expressed by Gartner [8]). This position confirms the view that having one's own business is associated with independence [5]. Some of them did not know where to seek help within the university, while others did not receive the financial support necessary to develop their business (Q8)(cf. [26]). For these reasons, they do not plan to use UITM support in the future. Women emphasize that they prefer the market offer, which better meets their needs, while men point to the lack of an attractive support offer from the university (Q8). The

second group consists of students who do not run businesses (Q1_2), do not use UITM support (Q3_2), and do not plan to use it in the future (Q6_2). English-speaking students indicated that the lack of access to finance was the reason for not using UITM's support. They believe that the university's business support offer is neither attractive nor adequate to their expectations (Q8) (cf. [11]). Second-cycle students who did not start a business and do not plan to use support from UITM justify their decision with the desire to avoid obligations to the university in a future (Q8) (cf. [15]).

6. Conclusion

This paper presents a new approach to data analysis that accounts for uncertainty and missing questionnaire responses. By utilizing Łukasiewicz's three-valued logic and transforming the set of values to $\{-1, 0, 1\}$, the method enables the modeling of not only unambiguous states (true/false) but also responses expressed as *I don't know*. The approach, which determines the adjacency matrix through the implication operator, allows for the identification and quantitative representation of relationships between variables, even in cases of missing data. The proposed method focuses not on the classic input–output model but on measuring the degree of confirmation of the relationship between attributes (questions) and respondents' decisions.

The methodology was validated on data collected in a representative study of university support for student entrepreneurship, which was based on an original psychometric test conducted on a sample of 1,526 students. The obtained results are reliable and consistent with the positions presented in the economic literature on the studied issues. This methodology addresses the challenge of limiting data sets due to incomplete questionnaires, thus preventing their exclusion from the research.

In future research, we plan to extend our approach to model uncertainty arising from ambiguity or subjective interpretation of data using the proposed hybrid fuzzy-rough method [19]. In particular, we aim to address uncertainty present in public opinion surveys, caused by vague terms such as often or many, which can be interpreted in various ways. Additionally, using the resulting IMP matrix and its associated coefficients, we plan to conduct statistical analyses to assess the strength and stability of the detected dependencies.

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