Politechnika Częstochowska
Wydział Zarządzania

Zeszyty Naukowe Politechniki Częstochowskiej. Zarządzanie
Research Reviews of Czestochowa University of Technology. Management

No 48 (2022), pp. 100-112, ISSN: 2083-1560
DOI: 10.17512/znpcz.2022.4.08, https://znz.pcz.pl/

Received: 15.09.2022; Revised: 20.11.2022;
Accepted: 23.11.2022; Published: 30.12.2022.

DEMPSTER–SHAFER THEORY FOR RISK ASSESSMENT IN PROJECT MANAGEMENT

Joanna Łabędzka[1*]

[1] Jan Kochanowski University in Kielce, Faculty of Law and Social Sciences, Poland

Abstract: Project management (PM) involves decision-making processes related to reaching project goals, resources allocation, timelines, intended outputs, outcomes, long-term impacts, etc. Decisions create challenges for those involved in leading and managing projects, such as information overload, time constraints, uncertainty, and biases. Decision-making in PM is especially supported by risk analysis focused on the identification and assessment of factors that could affect (positively or negatively) a successful project delivery. Uncertainty in estimating project risks is considered one of the major challenges in Management Science. The paper draws attention to the root cause of uncertainty in human reasoning in relation to decision-making processes with particular emphasis on risk analysis. A literature review revealed that the area of risk assessment in PM has been dominated by qualitative methods that do not take uncertainty into account. Therefore, the main objective of this paper was to apply the Dempster–Shafer theory (DST), which provides a framework for representing uncertainties by allowing beliefs to not be assigned to a specific subset. Accordingly, the applied research design was employed in this study. The research sample included 60 experts that assessed project risks. In order to determine the belief (Bel) and plausibility (Pl) functions, all the evidence was combined using Dempster's rule of combination, in order to arrive at quantified beliefs. The final results of the study showed that this evidence-based framework for project risk assessment is applicable and easy to use, even for a large number of experts and could support PM practitioners in risk management and decision-making.

Keywords: Dempster–Shafer theory, project management, risk assessment, uncertainty

JEL classification: D81, O22

[1] Joanna Łabędzka, PhD, ul. Uniwersytecka 15, 25-406 Kielce, Poland, joanna.labedzka@ujk.edu.pl, https://orcid.org/0000-0003-1409-7926
* Corresponding author: Joanna Łabędzka, joanna.labedzka@ujk.edu.pl

DOI: 10.17512/znpcz.2022.4.08

Introduction

Efficient project management can accelerate business growth by designing a clear, easy-to-follow path towards completing its objectives and goals. The literature is quite consistent in terms of defining project management. One of the widely known definitions states that project management (PM) is 'the application of processes, methods, skills, knowledge and experience to achieve specific project objectives according to the project acceptance criteria within agreed parameters' (Murray--Webster & Dalcher, 2019). Throughout the project life cycle (PLC), numerous decisions must be made; therefore, the ability to make informed, challenging, timely and effective decisions is seen as a key competency of the project manager.

Despite numerous methods, tools, and methodologies used for this purpose, knowledge and experience are put at the heart of the process. Due to its nature, origin, and limits, human knowledge is uncertain, inexact, and partial (Monk, 1999). Therefore, the underestimation of expert knowledge when creating the basis for decision-making may lead to erroneous analysis results (Labedzka et al., 2022). In project management, risk assessment plays an extremely important role as it empowers businesses with the necessary knowledge for decision-making so that a proper risk mitigation approach could be developed in an organisation (Campbell, 2014). The prevailing perspectives and definitions of risk, at least in the engineering community, are based on probabilities (Aven, 2010). The main purpose of risk analysis defined in this way is to accurately estimate risk, although the number does not express the truth, but is a judgment based on modelling and analysis, which could be supported by more or less strong knowledge (Aven, 2020). In this paper, project risk is understood as 'an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives such as scope, schedule, cost, and quality' (Hillson, 2014). A project risk assessment is a process of identifying and analysing risks in a manner that the risks are understood easier and managed more effectively (Barghi & Shadrokh Sikari, 2020).

Risk identification is arguably the most important phase of PM (Opara, 2020), since any risk not explicitly identified is taken unconsciously (Hillson, 2000). Risk assessment and any other decision points are exposed to various inconveniences, such as lack of knowledge, skills and/or experience, time pressure, inaccurate data, and having to choose between intuition and facts. In addition, human decision-making, also within project management, always takes place in an uncertain complex and dynamic environment.

Project risk assessment in practice must often integrate an objective fact-based analysis with a subjective human-centric input. Thus, in management science, psychology, decision science, and computer science, there is space for creating and using models and methods that not only seek to meet critical needs but can improve decision-making by dealing with uncertainty that is naturally attached to human knowledge and exists in all projects' environment.

The main contribution of the study is the original framework for the application of the Dempster–Shafer theory (DST) to the risk assessment of the project. The final results of empirical research showed that this evidence-based approach to risk assessment is applicable and easy to use, even for a large number of experts, and could support PM practitioners in risk management and decision-making.

Research Methodology

The Dempster–Shafer theory is intended for expressing uncertainty that characterises human reasoning and assessment and has been so far successfully used in manufacturing systems, maritime and offshore applications, diagnostics of technological processes, medicine, materials and products, building and construction, and quality control. The presented research attempts to expand the portfolio of its applications. The main objectives of this paper are as follows:

- to congregate and synthesise the literature review of issues related to a qualitative and quantitative project risk assessment with special attention paid to the ability to represent knowledge under uncertainty conditions; and,
- to present and apply the Dempster–Shafer theory to make risk assessment in project management more objective and less uncertain.

Thus, the research questions are as follows.

Q1: What methods are used for risk assessment in project management and do they relate to uncertainty?

Q2: How can the Dempster–Shafer theory be applied to risk assessment in project management?

The questions are tackled in two stages: theoretical and analytical. The first stage of the research involves the identification of literature by searching selected databases and Internet resources. For this work, the author carried out a systematic review of the most commonly-used databases that contain the greatest and most authoritative collections of journals, books, and research resources, i.e. Web of Science and Science Direct. According to the objectives and intentions of the research, the keywords selected were "project risk", "risk assessment", "project management", "uncertainty", and "methods", which were then combined and explored.

The theoretical part of the study highlights the root cause of uncertainty in human reasoning in relation to decision-making processes, with special attention paid to risk analysis. The definitions of project management, project risk and risk assessment are presented to ensure the clarity of the research following. Then a comprehensive review of methods for risk assessment that are used in project management is introduced. This task was accomplished by a series of analysis approaches, such as literature bibliometrics and desk research, and the findings of previously published articles.

In the second part of the paper, following the results obtained in the first part, main contributions related to the application of the Dempster–Shafer theory for project risk assessment are presented. The research sample included 60 experts, i.e., management and logistics students, who participated in risks assessment for the exemplar project 'Implementation of an augmented reality method in teaching in university courses'. In this part, the applied research used data collection, modelling, and analysis to extract insights that support decision-making for PM purposes.

In the preparatory stage, risks were identified on the basis of literature on common project risks that affect the successful implementation of the project. The risks were then discussed through brainstorming and three risks were selected by experts through the voting procedure. As the methodology of risk identification is not the subject of this paper, it is only mentioned above.

In the next step, a distribution of mass, which corresponds to the opinion of an expert was defined. Then, all the evidence was combined using Dempster's rule of combination to arrive at quantified beliefs that can support risk management and decision-making in project management.

Based on the above, this research aimed to justify the application of the DST to expert risk assessment to produce objective hints for decision-makers and increase the acceptability and repeatability of results. Finally, the concluding remarks and future research directions were presented.

State-of-the-art project risk assessment methods

One of the most difficult decisions in PM when analysing risks is to determine the most appropriate assessment method that could make the highest contribution to the project and would make the best of risk-related data available. There are many alternative methods to assist in identifying project risks; however, qualitative and quantitative analysis are the most widely known. Qualitative risk assessment methods (Table 1) express likelihood estimates in numerical ranking scales or descriptive, non-numerical terms such as high, medium, low, or negligible, and use simple approximate values (Cobb & MacDiarmid, 2014; Hillson, 2000).

Table 1. Examples of quantitative methods commonly used for risk assessment in PM

Method	Description	Limitations
Risk assessment matrix	Assigns risk ratings to risks or conditions based on combining probability and impact scales. Risks with high probability and high impact are likely to require further analysis, including quantification and aggressive risk management (Kremljak, 2011)	Categorising the severity and likelihood of uncertain risks is often subjective and therefore not totally reliable. If the blocks of the risk matrix are incorrectly grouped, then incorrect conclusions can be drawn about the relative risk presented by events at a facility (Elmontsri, 2014)
Bowtie Model	Provides a way to effectively communicate complex risk scenarios in an easy-to-understand graphical format and shows the relationship between the causes of unwanted events and the escalation potential for loss and damage (Voicu et al., 2018)	The credibility of quantitative evaluation of the bow-tie is still a major concern since uncertainty, due to limited or missing data, often restricts the performance of analysis (Ferdous et al., 2012)

Delphi Technique	A scientific method to organise and manage structured group communication processes with the aim of generating insights on current or prospective challenges; especially in situations with limited availability of information (Beiderbeck et al., 2021)	Using the method only for long-term forecasts, which postpones their verification (Cieślak, 1997)

Source: The author's own compilation based on research

On the other hand, the quantitative risk approach (Table 2) uses hard metrics and is defined as more objective than the qualitative one (Conrad et al., 2017).

Table 2. Examples of quantitative methods used for risk assessment in PM

Method	Description	Limitations
Probability Theory	Combines expert opinions, which are essential to the quantification process, with experimental results and statistical observations to produce quantitative measures of the risks from these systems (Apostolakis, 1990)	Does not express the truth or what will happen in the future, but is a judgment based on modelling and analysis, which could be supported by more or less strong knowledge; not capable of capturing epistemic uncertainty (Aven, 2020)
Analytic Hierarchy Process	Provides group decision-making through consensus using the geometric mean of the individual judgments; has the capability to check and reduce the inconsistency of expert judgments (Aminbakhsh et al., 2013)	The large number of judgments required often causes an inconsistency problem and when new alternatives are added to AHP, the assessments done on the old alternatives have to be discarded (Taroun & Yang, 2011)
Expected Monetary Value	Quantifies risks by multiplying the value of each possible outcome (impact) by its probability of occurrence and adding the products together (Gump, 2001)	Gives realistic results when there is a large number of risks in the project in large and complex projects (Expected Monetary Value, 2020)

Source: The author's own compilation based on research

Although quantitative data are difficult to collect because it is an expensive and time-consuming process, this kind of approach provides a more objective and accurate outcome. Quantitative research is also preferred over qualitative research because it is more scientific, objective, fast, focused and acceptable. However, presented mathematical formalisms for project risk assessment lose their justification, when input data from experts are uncertain, incomplete, and/or imprecise.

A combined approach to enhance the effectiveness and efficiency of the risk assessment process to integrate objective fact-based analysis with subjective human-centric input is also present in the literature and PM practice (Cohen, 2005; Cobb & MacDiarmid, 2014; Volkan, 2021). However, the application of the above-mentioned methods does not embrace the uncertainty that expert knowledge is burdened with.

The literature review agrees in general on the theoretical relevance of risk assessment. It can be stated with confidence that uncertainty exists in all projects, and appropriate methods should be employed to deal with this uncertainty and to reduce its impact on managers' decision-making (Barghi & Shadrokh Sikari, 2020).

Hence, in terms of the first research question (Q1): What methods are used for risk assessment in project management and do they relate to uncertainty? – it can be stated that a key understanding is to acknowledge that the limitations and criticisms of methods commonly used in project management for risk assessment, when attempting to consider uncertainty, express the challenge of representing any uncertainty associated with an expert's subjective belief.

As mentioned above, there is notable research on risk assessment. However, to the best of the author's knowledge, none of the studies considered the Dempster–Shafer theory for risk assessment using such a significant research sample and sharing the same methodology. This has been a motivation for the current work.

Dempster–Shafer theory of evidence (DST)

The Dempster–Shafer theory can be interpreted as an extension of the classical theory of probability by eliminating the requirement of knowing the complete space of elementary events (lack of full knowledge). This reasoning based on the mathematical theory of evidence intends to determine the basic probability assignment (bpa) known as the mass function denoted by the letter m, the belief function (Bel) and the plausibility function (Pl). It was introduced in the 1960s as a representation of reasoning under epistemic knowledge uncertainty by mathematician Arthur Dempster (Dempster, 1967), and described by Glenn Shafer (Shafer, 1976).

The DST is a potentially valuable tool for the evaluation of risk and reliability in engineering applications when it is not possible to obtain a precise measurement from experiments, or when knowledge is obtained from expert elicitation (Sentz & Ferson, 2002). It is especially useful in situations where each piece of evidence implies multiple candidate conclusions, and the support for each conclusion is computed from the overlapping contributions of diverse pieces of evidence to reflect the relative state of ignorance in the face of incomplete information, unlike classical probability theory (Das, 2003).

The key concept of the Dempster–Shafer theory is the finite set of all hypotheses called the frame of discernment Θ. It includes all states concerning the investigated problem, solution, domain, etc. Each subset of Θ has a degree of certainty assigned, which means that there is a true hypothesis in the given set represented by a function called basic probability assignment. For example, when assessing risk, Θ would be the set consisting of all possible risk rating levels. The power set 2^{Θ} is the set of all possible subsets of Θ including the empty set Φ. For example, if

$$\Theta = \{a, b\} \tag{1}$$

then,

$$2^{\Theta} = \{\varphi, \{a\}, \{b\}, \Theta\} \tag{2}$$

Individual elements of the power set represent propositions in the domain that may be of interest (Chen et al., 2014).

One of the most important functions in the Dempster–Shafer theory to define belief measure and plausible measure is known as basic probability assignment that over a finite set Θ is expressed as a function m that for $\forall A \subseteq \Theta$ satisfies the following axioms:

$$m(A) \geq 0 \tag{3}$$

$$m(\varnothing) = 0 \tag{4}$$

$$\sum_{X \in \Theta} m(A) = 1 \tag{5}$$

The quantity m(A) is the measure of the probability that is committed exactly to A, so it expresses the proportion of available evidence that supports the claim that the actual state belongs to A but not to any subset of A (Chen et al., 2014). The interpretation of the mass of the universal set (A) is the degree of ignorance.

The Dempster rule of combination (DRC) is used to determine uncertainty in subsets of hypotheses A and B formulated by different experts. DRC is concerned with the uniting of two independent sets of mass functions in a frame of discernment Θ. If Θ is a frame of discernment, and m_1 and m_2 are basic probability assignments, the combined mass $m_1 \oplus m_2$ it is a function $2^{\Theta} \rightarrow [0,1]$ where:

$$m_1 \oplus m_2(\varnothing) = 0 \tag{6}$$

$$m_1 \oplus m_2(C) = \frac{\sum_{A \cap B = C} m_1(A) \bullet m_2(B)}{1 - \sum_{A \cap B = \varnothing} m_1(A) \bullet m_2(B)} \tag{7}$$

for each A, B, $C \subseteq \Theta$ and A, $C \neq \varnothing$.

Equation (7) expresses the agreement between multiple sources of information and ignores conflicting evidence by using a normalisation factor calculated in the denominator of the formula. The result of the Dempster combination enables one to determine the belief function (Bel) and the plausibility function (Pl).

For a set of hypotheses A, where $\forall A \subseteq \Theta$, the following functions are defined:

a) belief function that represents the degree of belief in A, based on available evidence:

$$Bel(A) = \sum_{B \subseteq A} m(B) \tag{8}$$

b) plausibility function that represents a measure of evidence against A:

$$Pl(A) = \sum_{B \cap A \neq \emptyset} m(B) \qquad (9)$$

The degree of the belief function and degree of plausibility function are related to each other as follows:

$$Pl(A) = 1 - Bel(\neg A) \qquad (10)$$

The literature highlights numerous advantages of the Dempster–Shafer mathematical formalism to model ignorance understood as a lack of knowledge. (Gordon & Shortliffe, 1984) pointed out that DST over other approaches shows the ability to model the narrowing of the hypothesis set with the accumulation of evidence. Because of this feature, the theory is commonly used in expert reasoning and computer systems supporting decision-making. Its flexibility in modelling information, as classifiers can be created for solving any given problem, and mass functions can be as simple or as complex as required (Qi et al., 2014). It provides a convenient and simple mechanism for combining two or more pieces of evidence under certain conditions and can model ignorance explicitly (Liu et al., 2002). The Dempster–Shafer theory is, in comparison with the fuzzy set theory and the probability theory, richer in terms of semantics. There is no best theory to handle uncertainty (Taroun & Yang, 2011), and its definite advantage is that no a priori knowledge is required, making it potentially suitable for classifying previously unseen information (Kordy et al., 2016).

Dempster–Shafer theory for project risk assessment

In this part of the paper, a mathematical representation of uncertainty of expert knowledge is used to create the allocation of probability mass to both individual premises and sets of premises. The risk assessment values used are strongly related to expert knowledge. Thanks to the application of the Dempster–Shafer theory, the most probable risk mitigation and management decisions for a project can be determined on the basis of a subset of risks and a subset of their impact rating levels.

Expert knowledge on risk assessment for the project 'Implementation of an augmented reality method in teaching in university courses' was collected from 60 university students of management and logistics. In the first stage, risks were identified through brainstorming on the basis of literature on common project risks and described. Then three risks were selected by experts through the voting procedure. The following project risks were taken into further investigation:

- skills resource (pr_1);
- communication (pr_2); and
- technology risk (pr_3).

According to the risk management matrix, risk was assessed through rating and classifying: high (i_1), medium (i_2), low (i_3) risk based on the impact on the project. The students determined the probability of rating levels i_1, i_2, i_3 of the identified project risks pr_1, pr_2, pr_3. Thus, the discriminating frame Θ contains all the impacts of risks for the project:

$$\Theta = \{i^{pr1}_1, i^{pr1}_2, i^{pr1}_3, i^{pr2}_1, i^{pr2}_2, i^{pr2}_3, i^{pr3}_1, i^{pr3}_2, i^{pr3}_3\} \qquad (11)$$

In order to determine the belief (Bel) and plausibility (Pl) functions, calculations were made to combine data from all sixty students $s_1 – s_{60}$. The first step was to combine the data from the students s_1 and s_2 for the risk pr_1 (Table 3), where m is a basic probability assignment function.

Table 3. Partial results – combining data from experts s_1 and s_2

s_1 \ s_2		$m_2(i^1_1)$	$m_2(i^1_2)$	$m_2(i^1_3)$	$m_2(\Theta)$
		0.2	**0.4**	**0.2**	**0.2**
$m_1(i^1_1)$	**0.4**	0.08	0.16	0.2	0.08
$m_1(i^1_2)$	**0.2**	0.04	0.08	0.04	0.04
$m_1(i^1_3)$	**0.2**	0.04	0.08	0.04	0.04
$m_1(\Theta)$	**0.2**	0.04	0.08	0.04	0.04

Source: The author's own elaboration based on the students' assessment

According to Equation (7) a normalisation factor (12) and Dempster combination (Table 4) were calculated:

$$1 – (0.04 + 0.04 + 0.16 + 0.08+ 0.2 + 0.04) = 0.56 \qquad (12)$$

Table 4. Partial results – combining data from experts s_1 and s_2

Assessment of the students s_1 and s_2	Calculations	Dempster combination
$m_{1,2}(i^1_1)$	0.08 + 0.04 + 0.08 = 0.2	0.36
$m_{1,2}(i^1_2)$	0.08 + 0.08 + 0.04 = 0.2	0.36
$m_{1,2}(i^1_3)$	0.04 + 0.04 + 0.04 = 0.12	0.21
$m_{1,2}(\Theta)$	0.04	0.07
		$\sum = 1$

Source: Author's own elaboration based on the students' assessment

Further, the data from the remaining 58 students were combined (Table 5).

Table 5. Combining data from experts s_{1}-s_{50} and s_{51}

$s_{1,\ldots,50}$ \ s_{51}		$m_{51}(i^1_1)$	$m_{51}(i^1_2)$	$m_{51}(i^1_3)$	$m_{51}(\Theta)$
		0.1	**0.3**	**0.2**	**0.4**
$m_{1,\ldots,50}(i^1_1)$	**0.51**	0.05	0.15	0.10	0.20
$m_{1,\ldots,50}(i^1_2)$	**0.38**	0.04	0.11	0.08	0.15
$m_{1,\ldots,50}(i^1_3)$	**0.12**	0.01	0.03	0.02	0.05
$m_{1,\ldots,50}(\Theta)$	**0.00**	0.00	0.00	0.00	0.00
Normalisation factor		**0.59**			
$s_{1,\ldots,51}$ \ s_{52}		$m_{52}(i^1_1)$	$m_{52}(i^1_2)$	$m_{52}(i^1_3)$	$m_{52}(\Theta)$
		0.2	**0.3**	**0.2**	**0.3**
$m_{1,\ldots,51}(i^1_1)$	**0.43**	0.09	0.13	0.09	0.13
$m_{1,\ldots,51}(i^1_2)$	**0.45**	0.09	0.13	0.09	0.13

$m_{1,...,51}(i^1_3)$	**0.12**	0.02	0.04	0.02	0.04
$m_{1,...,51}(\Theta)$	**0.00**	0.00	0.00	0.00	0.00
Normalisation factor		**0.54**			
s_{53} / $s_{1,...,52}$		**$m_{53}(i^1_1)$**	**$m_{53}(i^1_2)$**	**$m_{53}(i^1_3)$**	**$m_{53}(\Theta)$**
		0.1	**0.3**	**0.4**	**0.2**
$m_{1,...,52}(i^1_1)$	**0.51**	0.04	0.12	0.16	0.08
$m_{1,...,52}(i^1_2)$	**0.38**	0.05	0.15	0.20	0.10
$m_{1,...,52}(i^1_3)$	**0.12**	0.01	0.03	0.04	0.02
$m_{1,...,52}(\Theta)$	**0.00**	0.00	0.00	0.00	0.00
Normalisation factor		**0,43**			

Source: Author's own elaboration based on the students' assessment

All opinions were combined using the Dempster rule of combination in order to quantify the belief on each relation. The final results of the combination of data for project risk pr_1 and Bel and Pl functions are presented in Table 6.

Table 6. Final results – (Bel) and (Pl) functions for risk pr_1

Assessment of all students $s_{1,...,60}$	Calculations	Dempster combination	Bel	Pl
$m_{1,...,60}(i^1_1)$	0.09 + 0.05 = 0.14	0.30	0.3	0.3
$m_{1,...,60}(i^1_2)$	0.11 + 0.11 = 0.22	0.47	0.5	0.5
$m_{1,...,60}(i^1_3)$	0.05 + 0.05 = 0.1	0.21	0.2	0.2

Source: The author's own elaboration based on the students' assessment

The most probable impact that risk pr_1 will have on the project is i_2 (medium). Similar iterative calculations were performed for risks: pr_2 and pr_3 (Table 7).

Table 7. Final results – Functions (Bel) and (Pl) for risks pr_2 and pr_3

Assessment of the students s_1–s_{60}	Bel	Pl
$m_{1,...,60}(i^2_1)$	0.3	0.3
$m_{1,...,60}(i^2_2)$	0.5	0.5
$m_{1,...,60}(i^2_3)$	0.2	0.2
$m_{1,...,60}(i^3_1)$	0.5	0.5
$m_{1,...,60}(i^3_2)$	0.2	0.2
$m_{1,...,60}(i^3_3)$	0.1	0.1

Source: Author's own elaboration based on the students' assessment

To achieve decision support in PM, the degree of belief (Bel) and plausibility (Pl) of the impacts of project risks pr_1, pr_2 and pr_3 were determined. As a result, for each project risk, the hypothesis with the highest degree of belief (the most probable) was calculated: the impact i_2 for the risk pr_1, i_2 for pr_2, and i_1 for pr_3.

Conclusions

In general, germane to the core decision are medium- and high-impact risks that can heavily influence the project's success. In the example presented, two medium impact risks (i.e. pr_1 and pr_2) were indicated within DST and these can be recognised as a potential threat or opportunity for the project execution. In addition, proposing preventive reactions to those risks helps to minimise the vulnerability exposure of the project and drive it towards a successful closure. Therefore, the presented research collected sufficient evidence for the second research question (Q2): How can the Dempster–Shafer theory be applied to risk assessment in project management? and justified the applicability of DST to risk assessment in PM.

To conclude, risk assessment is a tool to support the decision-making process and equip it with necessary information. In the research, the Dempster–Shafer theory is used to create a general framework for reasoning with uncertainty by combining possible opinions of experts regarding project risks to arrive at a result that is both more accurate and supported by the experts. It is particularly appealing in its potential for the combination of evidence obtained from multiple sources and the modelling of conflict between them.

The Dempster–Shafer theory might be also used to assess a large number and a wide range of risks with varied degrees of impact, probability of occurrence or other features. The final results of the study showed that such an evidence-based framework for risk assessment in project management might be an important support for practitioners, as it enables one to represent subjective uncertainty, produces outcomes that potentially satisfy both practical and emotional needs and increase decision-making opportunities.

The presented research has potential limitations. In the empirical part of the paper, risk assessment is based on the experts' rating. They are therefore subject to biases that may have influenced the final belief and plausibility functions. In turn, calculated Bel and Pl functions are crucial when selecting the most probable hypothesis regarding project risks with the highest impact.

To make project risk assessment more available and efficient, future research areas might be related to designing algorithms and more detailed holistic methodology with DST as a core approach. Furthermore, there is the potential to implement it within a computer program to automate project risk assessment.

References

Aminbakhsh, S., Gunduz, M., & Sonmez, R. (2013). Safety Risk Assessment Using Analytic Hierarchy Process (AHP) During Planning and Budgeting of Construction Projects. *Journal of Safety Research*, *46*, 99-105. DOI: 10.1016/j.jsr.2013.05.003

Apostolakis, G. (1990). The Concept of Probability in Safety Assessments of Technological Systems. *Science*, *250*(4986), 1359-1364. DOI: 10.1126/science.2255906

Aven, T. (2010). On How to Define, Understand and Describe Risk. *Reliability Engineering & System Safety*, *95*(6), 623-631. DOI: 10.1016/j.ress.2010.01.011

Aven, T. (2020). Risk Science Contributions: Three Illustrating Examples. *Risk Analysis*, *40*(10), 1889-1899. DOI: 10.1111/risa.13549

Barghi, B., & Shadrokh Sikari, S. (2020). Qualitative and Quantitative Project Risk Assessment Using a Hybrid PMBOK Model Developed under Uncertainty Conditions. *Heliyon*, *6*(1), e03097. DOI: 10.1016/j.heliyon.2019.e03097

Beiderbeck, D., Frevel, N., von der Gracht, H. A., Schmidt, S. L., & Schweitzer, V. M. (2021). Preparing, Conducting, and Analyzing Delphi Surveys: Cross-Disciplinary Practices, New Directions, and Advancements. *MethodsX*, *8*, 101401. DOI: 10.1016/j.mex.2021.101401

Campbell, G. K. (2014). Risk Assessment and Mitigation. In: G. K. Campbell (Ed.), *The Manager's Handbook for Business Security (Second Edition)* (pp. 29-39). Elsevier. DOI: 10.1016/B978-0-12-800062-5.00003-8

Chen, Q., Whitbrook, A., Aickelin, U., & Roadknight, C. (2014). Data Classification Using the Dempster–Shafer Method. *Journal of Experimental & Theoretical Artificial Intelligence*, *26*(4), 493-517.

Cieślak, M. (1997). *Prognozowanie gospodarcze. Metody i zastosowania*. Wydawnictwo Naukowe PWN.

Cobb, S. P., & MacDiarmid, S. C. (2014). Animal Health Risk Analysis. In: M. Dikeman, C. Devine (Eds.), *Encyclopedia of Meat Sciences (Second Edition)* (pp. 27-32). Academic Press. DOI: 10.1016/B978-0-12-384731-7.00163-X

Cohen, C. B. (2005). Project Management Decision Making: Blending Analysis and Intuition. *PMI® Global Congress 2005* – Latin America, Panama City, Panama. Project Management Institute.

Conrad, E., Misenar, S., & Feldman, J. (2017). Security Risk Management. In: E. Conrad, S. Misenar, J. Feldman (Eds.), *Eleventh Hour CISSP® (Third Edition)* (pp. 1-32). Syngress. DOI: 10.1016/B978-0-12-811248-9.00001-2

Cox, L., Babayev, D., & Huber, W. (2005). Some Limitations of Qualitative Risk Rating Systems. *Risk Analysis*, *25*(3), 651-662. DOI: 10.1111/j.1539-6924.2005.00615.x

Das, A. (2003). Knowledge Representation. In: H. Bidgoli (Ed.), *Encyclopedia of Information Systems* (pp. 33-41). Elsevier. DOI: 10.1016/B0-12-227240-4/00102-7

Dempster, A. P. (1967). Upper and Lower Probabilities Induced by a Multivalued Mapping. *The Annals of Mathematical Statistics*, *38*(2), 325-339. DOI: 10.1214/aoms/1177698950

Elmontsri, M. (2014). Review of the Strengths and Weaknesses of Risk Matrices. *Journal of Risk Analysis and Crisis Response*, *4*(1), 49-57.

Expected Monetary Value. (2020). *Project Cubicle*. https://www.projectcubicle.com/expected-monetary-value-emv-calculation

Ferdous, R., Khan, F., Sadiq, R., Amyotte, P., & Veitch, B. (2012). Handling and Updating Uncertain Information in Bow-Tie Analysis. *Journal of Loss Prevention in the Process Industries*, *25*(1), 8-19. DOI: 10.1016/j.jlp.2011.06.018

Gordon, J., & Shortliffe, E. H. (1984). The Dempster-Shafer Theory of Evidence. *Rule-Based Expert Systems: The MYCIN Experiments of the Stanford Heuristic Programming Project*, *3*, 832-838.

Gump, A. (2001). Using Decision Models in the Real World. *PM Network*, *15*(1), 43-45.

Hillson, D. (2000). Project Risks: Identifying Causes, Risks, and Effects. *PM Network*, *14*(9), 48-51.

Hillson, D. (2014). *Managing Overall Project Risk. PMI® Global Congress 2014 – EMEA, Dubai, United Arab Emirates*. Project Management Institute.

Kordy, B., Ekstedt, M., & Kim, D. S. (Ed.) (2016). *Graphical Models for Security: Third International Workshop, GraMSec 2016, Lisbon, Portugal*. Springer.

Kremljak, Z. (2011). Risk Management Methods – Project Risk. In: B. Katalinic (Ed.), *DAAAM International Scientific Book*, 10 (pp. 119-132). Publisher DAAAM International Vienna.

Labedzka, J., Poteralska, B., & Brozek, K. (2022). Computer-Based Knowledge Management for Futures Literacy, *12th International Scientific Conference "Business and Management 2022"*, May 12-13, 2022, Vilnius, Lithuania. DOI: 10.3846/bm.2022.808

Liu, J., Yang, J.-B., Wang, J., & Sii, H. S. (2002). Review of Uncertainty Reasoning Approaches as Guidance for Maritime and Offshore Safety-Based Assessment. *Journal of UK Safety and Reliability Society*, *23*(1), 63-80.

Monk, R. (1999). Cambridge Philosophers IX: Russell. *Philosophy*, *74*(287), 105-117. http://www.jstor.org/stable/3752096

Murray-Webster, R., & Dalcher, D. (2019). *APM Body of Knowledge* (7th ed.). Princes Risborough: Association for Project Management.

Opara, A. (2020). Ryzyko w zarządzaniu projektami – studium przypadku, *Zeszyty Naukowe Politechniki Częstochowskiej. Zarządzanie*, *39*, 7-14.
Sentz, K., & Ferson, S. (2002). *Combination of Evidence in Dempster-Shafer Theory, Sandia Report*. Sandia National Laboratories.
Shafer, G. (1976). *A Mathematical Theory of Evidence*. Princeton University Press.
Taroun, A., & Yang, J. B. (2011). Dempster-Shafer Theory of Evidence: Potential Usage for Decision Making and Risk Analysis in Construction Project Management. *The Built & Human Environment Review*, *4*(1), 87-97.
Voicu, I., Panaitescu, F. V., Panaitescu, M., Dumitrescu, L., & Turof, M. (2018). Risk Management with Bowtie Diagrams. *IOP Conference Series: Materials Science and Engineering*, *400*, 082021. DOI: 10.1088/1757-899X/400/8/082021
Volkan, E. (2021). *Risk Assessment and Analysis Methods: Qualitative and Quantitative*. https://www.isaca.org/resources/isaca-journal/issues/2021/volume-2/risk-assessment-and-analysis-methods

Authors' Contribution: 100%.

Conflict of Interest: The author declares no conflict of interest.

Acknowledgement of funding: This research was supported by the Jan Kochanowski University of Kielce [grant number SUPB.RN. 22.036 entitled 'Human Resources Development for the Needs of the Future']

TEORIA DEMPSTERA–SHAFERA W OCENIE RYZYKA W ZARZĄDZANIU PROJEKTAMI

Streszczenie: Zarządzanie projektami (ang. PM – Project Management) obejmuje procesy decyzyjne ukierunkowane m.in. na osiąganie celów projektu, alokację zasobów, realizację harmonogramu rzeczowo-finansowego, finalizowanie założonych krótko-, średnio- i długoterminowych rezultatów. Podejmowanie decyzji w PM jest szczególnie wspierane analizą ryzyka skoncentrowaną na identyfikacji i ocenie czynników, które mogą wpłynąć (pozytywnie lub negatywnie) na powodzenie projektu. Niepewność w szacowaniu ryzyka projektu jest uważana za jedno z głównych wyzwań w naukach o zarządzaniu. W artykule zwrócono uwagę na źródłową przyczynę niepewności ludzkiego rozumowania w odniesieniu do procesów decyzyjnych, ze szczególnym uwzględnieniem analizy ryzyka. Przegląd literatury w zakresie jakościowych i ilościowych metod oceny ryzyka stosowanych w PM wykazał, że praktyczny obszar oceny ryzyka jest zdominowany przez metody jakościowe, którym brak mechanizmów reprezentacji niepewności. Do oceny ryzyka projektowego zaproponowano zatem zastosowanie teorii Dempstera–Shafera (DST), która dostarcza aparatu matematycznego do reprezentacji niepewności wiedzy eksperckiej. W artykule przedstawiono szczegółowe dane dla 60 ekspertów. Dane od ekspertów złożono z wykorzystaniem reguły kombinacji Dempstera. Odpowiedni poziom przekonania uzyskano w wyniku pokrycia analizowanego zbioru wpływu ryzyka projektowego przez opinie eksperckie. Dodawanie kolejnych danych, pokrywających swym zasięgiem badane ryzyko projektowe, daje możliwość podniesienia poziomu przekonania o wielkości wpływu ryzyka na realizację projektu i stanowi cenne narzędzie wspomagania decyzji w zarządzaniu projektami.

Słowa kluczowe: ocena ryzyka, zarządzanie projektami, niepewność, teoria Dempstera–Shafera