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Fuzzy Optimization Models for Intellectual Capital Enhancing Project Portfolio Selection under Risk

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Abstract. This paper proposes fuzzy optimization models to select project portfolios that enhance an organization's intellectual capital taking risks into account. Fuzzy optimization models are proposed to support decision-making in the selection of project portfolios within the framework of an organization's intellectual capital development program. Intellectual capital is considered as a multi-level hierarchical system with numerous implicit factors. A scenario approach is applied to model internal and external conditions. The project's utility is defined as a change in integral indicator of an organization's intellectual capital resulting from its implementation. Measures of risk are based on the utility dispersions. The expected specific utility of the project portfolio, or the portfolio risk, is used as a fuzzy objective function. Constraints in the models are also fuzzy. Fuzzy optimization problems are converted to crisp Boolean quadratic programming problems. A distinctive feature of the models is the use of fuzzy inference systems to calculate the values of intellectual capital development indicators at different hierarchical levels. Exogenous variables in the models are represented as Gaussian-type fuzzy numbers. The results of approbation of the proposed models using the case of a large regional university are presented and discussed. Further research endeavors could involve testing the models using examples from other organizations to enhance practical recommendations for managers and substantiate the potential for scalability. Additionally, a more rigorous model diagnostics process is required.

Keywords: intellectual capital, fuzzy model, optimization model, project portfolio, utility function, scenario approach, fuzzy inference system.

1. Introduction

Intellectual capital (hereinafter referred to as IC) is a key driver of digital economy development. The development of IC in an organization occurs through the implementation of a specific set (portfolio) of projects (activities) that collectively constitute the IC development program. Development projects for IC compete for shared limited resources. Therefore, the challenge arises to formulate a program under resource constraints that ensures the maximum possible increase in the organization's IC.

The development of a program always occurs in conditions of uncertainty. Consequently, in solving the project selection problem, it is necessary to consider not only constraints on resources but also risks.

In the context of the instrumental component of portfolio optimization theory, a significant number of models and methods have been developed considering various factors and risks. The observed phenomenon is primarily attributed to the economic nature of IC as an implicit determinant in managerial actions. Additionally, the character of IC development is shaped by the influence of distinct concealed factors, the effects of which on the developmental processes are inherently implicit and challenging to formalize (Ding & Li, 2010; Nazarov, 2016). Moreover, IC represents a hierarchical system that encompasses the primary structural components of IC (human capital, organizational capital, relational capital), as well as types of cognitive activities (education, engagement, production rationalization, self-improvement, customer-oriented rationalization, innovation) related to these structural components (Zavalin et al., 2023a). It merits attention that the development of various types of organization’s IC is achieved through different cognitive activities (Nedoluzhko, 2016). Moreover, formalizing the impact of cognitive activities and their constituent factors on the development of diverse structural components of IC proves to be challenging.

The nature of certain constraints in project selection, significant challenges in quantifying many factors, the tendency of experts and decision-makers to use verbal assessments, and the necessity to evaluate and account for risks contribute to the increasing popularity of fuzzy portfolio investment models (Micán et al., 2020). The application of fuzzy models to IC appears particularly promising due to its economic nature and development characteristics.

Optimization models with fuzzy objective functions and constraints enable the variation of results when specifying different exogenously set confidence levels (Anshin, 2015). This provides decision-makers with greater flexibility, which is particularly crucial when selecting and planning an integrated portfolio of projects (Zhang et al., 2019). On the other hand, such models allow not only the consideration of the risks themselves but also the risk propensity of the decision-maker, which is expressed in various approaches to portfolio selection (Zhou, 2018).

Fuzzy optimization problems require specialized solution methods. However, the lack of examples demonstrating the application of the proposed methods to enhance the IC of specific organizations poses significant challenges to their further use.

In this regard, the following questions remain relevant:

- Development of fuzzy portfolio optimization models in the field of enhancing the IC of an organization, considering risks.
- Improvement of methods for solving fuzzy optimization problems.
- Demonstration of the use of models and methods through real-world examples.

2. Literature Review

Numerous approaches exist for optimizing intellectual capital (IC), depending on how it is defined, and which goals are pursued during its implementation. In accordance with the possible options, the following groups of scientific studies on IC optimization can be identified.

The first category comprises studies wherein a limited volume of financing is distributed among key components of IC or designated funding directions. Within this group, several subgroups can be distinguished.

The first subgroup includes studies in which researchers focus on finding the optimal allocation of the budget among potential investment directions. Thus, the study (Sokolyanskiy et al., 2015) introduces a model for optimizing the companies' IC associated with the IT sector of the economy. The objective function is formulated as a function of an n-dimensional vector argument, with the financial parameters related to the three IC components as the variable parameters. The article (Lisenkova et al., 2020) formulates and solves a multi-criteria problem of optimizing expenditures on IC components of high-tech Russian and foreign enterprises. The variable parameters are the costs of IC components, and the optimization problem is solved using the NGSA II evolutionary algorithm. The algorithm is based on ranking the population agents using non-dominated sorting. An alternative method involves transforming the multi-criteria problem into a single-criterion one. The authors construct models for IC elements and obtain the Pareto front to maximize their efficiency in the Rocket and Space Corporation "Energia" and Cobham companies. To simplify decision-making for the top management, the introduction of formal preference functions is proposed. In the study (Andrusenko et al., 2022), the problem of constrained optimization is addressed, wherein the variable parameters correspond to expenditure items. The scalar objective function is the sum of functions formalizing the monetary equivalents of human, organizational, and consumer capitals. Computational experiments are conducted for several IT companies using both a genetic algorithm and a particle swarm algorithm.

In the works of the second subgroup, the derived solutions enabling an optimal resource allocation among investment directions may serve as a foundation for developing a set of strategies for investing in IC. These strategies consider not only the potential investment directions, but also more detailed characteristics of their implementation, such as the timing of investments or possible sequences of activities within each direction. For example, the work (Morimatsu & Takahashi, 2022) addresses the problem of allocating financing among three IC components is addressed. Based on this, a decision can be made regarding the selection of one of the potential strategies – challenging a new market or remaining in the current market with subsequent evaluation of the market situation and determination of competitive conditions.

The second group of works can be attributed to the optimization of project portfolios aimed at enhancing an organization's IC. H. Daniels and his co-authors have made a significant contribution to this research direction (Daniels & de Jonge, 2003; Daniels & Noordhuis, 2002; Daniels & Smits, 2005).

In the paper (Daniels & Noordhuis, 2002) three key characteristics of IC, which are significant in terms of methods for its assessment and management, are examined. Among them, the authors distinguish highly invariable capacity, a zero-profit target, and a constant need to develop new valuable knowledge. This leads them to conclude the necessity of using non-monetary methods for IC assessment, with their preferred options being the Intangibles Assets Monitor model by K.-E. Sveiby, Scandia Navigator, and the Balanced Scorecard (BSC). All of them, to some extent, are suitable for selecting IC performance indicators and subsequently evaluating their current values and setting target values. Target indicator values within the model are determined through expert assessment. The optimization model proposed by the authors becomes converted to a standard Boolean linear programming problem with constraints on the number of person-hours presumed to be consumed in the context of each IC optimization activity. The objective function considered is a scoring evaluation of IC.

The work (Daniels & B. de Jonge, 2003) proposes five perspectives of IC scorecards: financial, customer, process, human resources, and innovation perspectives. The key distinction of this model from the previous one lies in the consideration of risks associated with project implementation. Risk values are also expertly assessed in points.

In the work (Daniels & Smits, 2005) a multi-criteria model is proposed, allowing the identification of sets of non-dominated (Pareto-optimal) solutions, representing a set of feasible project portfolios. In this context, the utility of the project portfolio can be considered in terms of maximizing value, strategic fit, or portfolio balance (in terms of project duration, risk levels, and economic value diversity).

A model for optimizing the project portfolio aimed at enhancing the IC of a small enterprise is proposed in the article (Berezovskaya & Kryukov, 2009). The objective function is constructed using scoring assessments for the degree of target values achievement for indicators characterizing each of the four key IC components – human capital, structural capital, innovation capital, and customer capital. Constraints in the model are imposed regarding project labour costs.

In the paper (Stepanova & Stupak, 2022) a model of discrete linear programming is proposed. The objective function is represented as a utility function formed by the method of additive convolution, with constraints on resources. The utility function is formed as a weighted sum of components related to sustainable growth, update, and efficient utilization of human, organizational, and consumer capitals. The study does not provide a decomposition of the components into lower-level hierarchy constituents, as well as approbation of the presented model.

The limited number of publications dedicated to project portfolio optimization for enhancing an organization's IC is partially compensated by the works that explore portfolio optimization with respect to the individual core structural components of IC – human, organizational, and relational capital.

A significant number of various optimization models for human capital development are proposed in the works of L.S. Mazelis and colleagues. Some of the works are devoted to solving the problem of determining the optimal structure of investments in human capital (Mazelis et al., 2021; Mazelis et al., 2020c).

Other works are devoted to the project portfolio optimization aimed at enhancing human capital. In the study conducted by Mazelis et al. (2017), a dynamic model is formulated for devising an optimal plan for strategic activities in the enhancement of human capital within the business units of the university. In the article (Mazelis & Lavrenyuk, 2017) this problem is described in a fuzzy framework. In the work (Mazelis et al, 2019) a similar problem is addressed at the meso-level (regional level). In the research (Mazelis et al, 2020b) a two-level model for forming an optimal portfolio of projects to achieve regional development goals is developed. The model considers the influence of investments in regional human capital on its development level and the impact of the region's human capital development on the overall level of socio-economic development of the region. The same model in a fuzzy setting is described in the work (Mazelis et al., 2020a). The work (Abbasianjahromi & Hosseini, 2019) provides a model for employing human resources in construction projects with the risk-cost optimization approach. The model is formulated through the utilization of zero–one non-linear programming. The paper (Cheng, 2022) introduces a portfolio model that formulates a human resources portfolio based on a a neuro-fuzzy approach. A neuro-fuzzy system uses the simulated annealing algorithm to interpret the Boston Consulting Group portfolio matrix.

The development of an organizational capital is significantly achieved through the rationalization of production processes. In this regard, the following works can be attributed to portfolio optimization in relation to organizational capital. In the article (Martynov, 2011) the problem of optimizing the portfolio of technical solutions using discrete programming methods is addressed. In the work (Tretyakov et al., 2013), a model for project portfolio optimization for the development of the production complex is proposed. It is noteworthy that the latter model is applicable not only to the advancement of organizational capital but also to the optimization of relational capital. The assessment of relational capital levels is conducted through a competitiveness index, which characterizes the investment and innovation activities of the production complex. The development of this model and its approbation using the example of the energy machine-building complex is discussed in the article (Krivorotov et al., 2018). The study (Salehi et al., 2023) introduces a novel model designed to optimize Research and Development (R&D) project portfolios within the context of a decentralized decision-making structure within a pharmaceutical holding company. The presented decentralized optimization model utilizes a bi-level framework and incorporates a mixed-integer follower model for network design. In the bi-level programming model, the upper-level variables encompass the cash amount within the holding company's account and the budget allocation, representing the amount of budget assigned to each follower and determined by the leader. At the lower level, each subsidiary responds to the allocated budget and decides on its portfolio scheduling. The article (Fernandez et al., 2019) proposes a model of the time-related effects, influenced by imperfect knowledge, in the selection of optimal portfolios for new product development. The proposed approach employs an interval-based method to address new product development portfolio optimization issues arising from various forms of imperfect knowledge. The multi-objective optimization problem is tackled using the interval-based evolutionary algorithm I-NSGAII, capable of approximating the Pareto frontier within the interval domain. The paper (Zhang & Liu, 2023) illustrates a pharmaceutical R&D portfolio optimization model aiming to minimize borrowed capital while considering corporate strategy in new product development. The model accounts for resource scarcity, budgetary constraints, and a cardinality constraint. The proposed bi-objective model, focusing on maximizing terminal wealth and minimizing cumulative borrowed capital, is transformed into a single-objective model using the weighted sum approach and is optimized using the modified artificial bee colony (MABC) algorithm. The article (Bortoluzzi & Furlan, 2021) introduces a multi-criteria model designed to facilitate decision-making in technology selection for Distributed Generation of Energy (DGE) projects within a portfolio. The decision model incorporates multi-criteria methodologies to aid in the evaluation, prioritization, and selection of projects within a multistage decision-making process aligned with the strategic management cycle. The over-classification techniques Preference Ranking Organization Technique for Enrichment Evaluations (PROMETHEE) II and V are applied within the Value-Focused Thinking (VFT) approach, reflecting the preferences of decision-makers or managers among conflicting criteria in the investment context of sustainable distributed energy generation projects.

Development of relational capital in an organization is achieved through the formation of a complex network of relationships and interactions with its stakeholders. Due to this, when making decisions regarding the project portfolio selection, the specific interests of different stakeholder groups, their explicit and implicit objectives, as well as broader aspects of strategic value, such as social, environmental value, or knowledge value, may be considered (Ang et al., 2015; Rojas & Liu, 2015). The work (Kononenko & Korchakova, 2022) presents a model of optimization in which the objective function is a social effect of the project portfolio, such as improving the qualifications and wages of the personnel, addressing social issues of the collective or other communities associated with these projects. A fuzzy optimization model of the organization's project portfolio, allowing for the consideration of social significance and state importance of projects, is proposed in the article (Volgina et al., 2016). Fuzzy models for project portfolio optimization of an organization, allowing to consider the interests and requirements of a wide range of stakeholders, are developed in the works (Likhosherst et al., 2017; Likhosherst et al., 2019).

Within the framework of solving the goal of organization’s IC development, the use of portfolio optimization models concerning individual structural components is complicated by the fact that the implementation of individual projects may contribute to the development of not a single structural component, but two or even all three. Some of the lowest-level IC indicators serve as drivers for the development of various cognitive activities corresponding to different structural IC components. In this regard, there arises a need for the development of portfolio optimization models for IC as a unified hierarchical system. Moreover, the presence of a significant number of implicit factors and challenging-to-formalize dependencies between elements of different hierarchy levels necessitates the construction of fuzzy optimization models.

Hence, the aim of this study is to develop and test fuzzy project portfolio optimization models to enhance the IC as a hierarchical system, considering risks.

3. Models

Within this paper, the problem of the project portfolio optimization for enhancing the organization’s intellectual capital (IC) is discussed, considering risks and investment volume constraint. It is assumed that causal field of IC development indicators is shaped and represented in the form of a hierarchical structure (Zavalin et al., 2023b; Zavalin & Solodukhin, 2023). In this hierarchy, the root vertex (zero level) is the integral indicator of an organization's IC (I). The first level is represented by three key IC indicators, which correspond to the main structural IC components: human capital (I_1), organizational capital (I_2), and relational capital (I_3). At the second level, there are integrated indicators corresponding to types of cognitive activities: education (I_{11}), self-improvement (I_{12}), involvement (I_{21}), production rationalization (I_{22}), customer-oriented rationalization (I_{31}), and innovation (I_{32}). On the following level, subgroups of IC factors are identified, corresponding to specific aspects within individual types of cognitive activities: research (I_{121}), socio-psychological (I_{122}), digital (I_{221} and I_{312}), infrastructure (I_{122}), qualification (I_{322}), reputation (I_{313}), entrepreneurial (I_{311}), as well as aspects of interaction with partners (I_{223} and I_{321}). The lowest-level of the hierarchy is formed by explicit and implicit IC factors grouped into their respective subgroups.

Some of the lowest-level IC indicators are assessed on quantitative scales (these will be referred to as “quantitative” indicators). The other part is qualitative (these will be referred to as “qualitative” indicators).

“Qualitative” IC indicators are evaluated by the experts using a predefined linguistic scale and are transformed into fuzzy sets based on specified membership functions, for instance, trapezoidal.

Expert responses should be checked for consistency (Nazarov, 2016) and then averaged. Each expert can be assigned a crisp or fuzzy weighting coefficient reflecting their level of competence. In this case, the weighted average expert assessments are calculated.

There are various ways to implement fuzzy arithmetic. In this study, a unified system of rules for performing arithmetic operations over the (L-R)-type fuzzy numbers is used (Raskin & Sira, 2020). When using this rule system, the aggregated expert assessments of “qualitative” IC indicators can have exponential (Gaussian) membership functions (more precisely, the membership functions of the resulting fuzzy sets are very well approximated by Gaussians).

“Quantitative” IC indicators do not require expert assessments (and, therefore, procedures for checking consistency and averaging), since their quantitative values are known. These values are typically obtainable from the organization's management accounting data. The fuzzification of these indicators requires individual assignment of fuzzy set membership functions for the values of linguistic scales for each individual “quantitative” indicator. For simplicity and convenience, a common linguistic scale can be chosen for all “quantitative” indicators. However, the supports and membership functions of the corresponding fuzzy sets for different “quantitative” indicators may differ.

Moving upwards the hierarchy, we can obtain fuzzy values for all indicators of IC development. To achieve this, fuzzy inference systems may be employed, which include established bases of fuzzy production rules and fuzzy inference algorithms.

The utilization of such algorithms necessitates the construction of bases of fuzzy production rules. The antecedents in these fuzzy production rules are fuzzy propositions on the IC indicators values of the current hierarchy level. Subconclusions are fuzzy statements about the values of the IC indicators of the higher hierarchy level, which are the parent nodes for the indicators appearing in the subconditions. Fuzzy logic inference algorithms, applied to crisp values of input variables, enable the determination of a fuzzy value for the output variable, which can be defuzzified if necessary (i.e., a crisp value for the output variable can be determined).

In an organization, let there be N projects $P_1, P_2, \dots, P_N$ aimed at IC development, impacting K lowest-level IC development indicators $e_1, e_2, \dots, e_K$.

To model internal and external conditions, a scenario-based approach is applied: we consider L scenarios of potential changes in the internal and external environment $S_1, S_2, \dots, S_L$, each associated with fuzzy probabilities $p_1, p_2, \dots, p_L$ accordingly.

The probabilities of the scenarios are also assessed expertly on a certain linguistic scale and then transformed into fuzzy sets in accordance with specified membership functions. Expert assessments of scenario weights are further reviewed for consistency and averaged, accounting for expert weights. Consequently, the fuzzy probabilities of scenarios have membership functions close to Gaussians.

It is assumed that the implementation of each project leads to changes in the lowest-level IC development indicators and, through them, all IC indicators in the hierarchy. These changes may vary under different scenarios. Changes in lowest-level IC indicators are also determined by experts, followed by checking for consistency and averaging for individual scenarios. Thus, they are also Gaussian-type fuzzy numbers.

Based on fuzzy changes in indicators $e_1, e_2, \dots, e_K$, fuzzy changes in all IC indicators in the hierarchy, including the organization's integral IC indicator (*I*), can be calculated.

The number of financial resources required to implement a given project may also be expressed as a fuzzy number, calculated based on expert responses on a corresponding linguistic scale.

So, each of the projects P_n $(n = \overline{1, N})$ is characterized by the following indicators:

- The fuzzy changes $A_n^l = (a_{n1}^l, a_{n2}^l, \dots a_{nK}^l)$ in the indicators $e_1, e_2, \dots, e_K$ during the project implementation within the scenario S_l $(l = \overline{1, L})$.
- The fuzzy change I_n^l in indicator *I* during the project implementation within the scenario S_l.
- The fuzzy amount of financial resources required for its implementation B_n.

The value I_n^l can be considered as the utility of the project P_n within the scenario S_l.

We consider the changes $A_n^l = (a_{n1}^l, a_{n2}^l, \dots a_{nK}^l)$, and thus the utilities I_n^l as random variables depending on a series of external and internal factors that are functions of time. We use the utility dispersions DI_n^l as a measure of risk.

Let us define a binary variable y_n as following:

- y_n= 0, if project *n* is not included in the portfolio for enhancing the organization's IC.
- y_n= 1, if project *n* s included in the portfolio for enhancing the organization's IC.

The following scheme for constructing the optimal project portfolio to enhance the organization's IC is proposed:

1. For each project *n* we fuzzily determine the required volume of financial resources B_n needed for its implementation.

2. We define a set of scenarios $S_1, S_2, \dots, S_L$ and fuzzily estimate the probability of each of them $p_1, p_2, \dots, p_L$.

3. For each scenario *l* for each project *n* we determine fuzzy changes $A_n^l = (a_{n1}^l, a_{n2}^l, \dots a_{nK}^l)$ in indicators $e_1, e_2, \dots, e_K$ and calculate fuzzy utilities I_n^l.

4. We calculate the fuzzy specific utility of each project *n* within scenario *l* using the formula:

$$\tilde{I}_n^l = \frac{I_n^l}{B_n}. \quad (1)$$

5. We calculate the fuzzy mathematical expectation of the specific utility of project n within the scenario l:

$$m_n = E(\tilde{I}_n^l) = \sum_{l=1}^{L} \tilde{I}_n^l p_l. \quad (2)$$

and the fuzzy elements of the covariance matrix of specific utilities of projects *i* and *j*:

$$v_{ij} = \sum_{l=1}^{L} (\tilde{I}_i^l - m_i)(\tilde{I}_j^l - m_j) p_l. \quad (3)$$

The variable m_n represents the specific utility of project n.

6. We fuzzily set an upper limit B_0 based on the available financial resources.

7. Portfolio utility $m_{port} = \sum_{i=1}^{N} y_i m_i$, portfolio risk $\sigma_{port}^2 = \sum_{i,j=1}^{N} y_i y_j v_{ij}$.

Utilizing the assumptions, relationships, and notations introduced above, the building of a project portfolio aimed at enhancing the organization's IC is proposed to be carried out using the following models.

Model One. The project portfolio for enhancing the organization's IC is formed based on the criterion of maximizing the expected specific utility while adhering to constraints on the program's risk level and the financial resources required for portfolio implementation:

$$\begin{cases} \sum_{i=1}^{N} y_i m_i \rightarrow max \\ \sum_{i,j=1}^{N} y_i y_j v_{ij} \leq \sigma_0^2, \\ \sum_{i=1}^{N} y_i B_i \leq B_0 . \end{cases} \quad (4)$$

Model Two. The project portfolio for enhancing the organization's IC is formed based on the criterion of minimizing portfolio risk under constraints on the volume of resources required for portfolio implementation and the expected specific utility:

$$\begin{cases} \sum_{i,j=1}^{N} y_i y_j v_{ij} \rightarrow min, \\ \sum_{i=1}^{N} y_i m_i \geq m_0, \\ \sum_{i=1}^{N} y_i B_i \leq B_0. \end{cases} \quad (5)$$

The formulated models represent fuzzy Boolean quadratic programming problems.

These problems are reduced to the crisp Boolean quadratic programming problems (6) and (7) using the techniques described in the works (Anshin et al., 2008; Dubois & Prade, 1988; Wang & Hwang, 2007).

$$\begin{cases} m \rightarrow max, \\ N_{\sum y_i m_i}(m, m, \infty, \infty) \geq \gamma, \\ N_{\sum y_i y_j v_{ij}}(\sigma_0^2) \geq \lambda_{\sigma^2}, \\ N_{\sum y_i B_i}(B_0) \geq \lambda_B, \\ y_i \in \{0,1\}. \end{cases} \quad (6)$$

$$\begin{cases} \sigma_0^2 \rightarrow min, \\ N_{\sum y_i y_j v_{ij}}(\infty, \infty, \sigma_0^2, \sigma_0^2) \geq \gamma \\ N_{\sum y_i m_i}(m_0) \geq \lambda_m, \\ N_{\sum y_i B_i}(B_0) \geq \lambda_B, \\ y_i \in \{0,1\}. \end{cases} \quad (7)$$

Here $N_A(B) \geq \gamma$ means that the fuzzy number A satisfies the fuzzy constraint B with a satisfaction degree γ. $\gamma, \lambda_{\sigma^2}, \lambda_m, \lambda_B$ are satisfaction degrees for the objective function and constraints on risk, utility and budget portfolio.

In this case, if $A =< a_1; a_2; a_3; a_4 >$ is a trapezoidal fuzzy number, and $B =< 0; 0; b_3; b_4 >$ is a trapezoidal fuzzy upper bound, then $N_A(B) \geq \gamma$ is equivalent to the inequation $(1-\gamma)a_3 + \gamma a_4 \leq \gamma b_3 + (1-\gamma)b_4$. If $B =< b_1; b_2; 0; 0 >$ is a trapezoidal fuzzy lower bound, then $N_A(B) \geq \gamma$ is equivalent to the inequation $\gamma a_1 + (1-\gamma)a_2 \geq (1-\gamma)b_1 + \gamma b_2$.

Such an approach to transitioning from fuzzy optimization problems to crisp ones has certain limitations. In particular, the conversion formula from fuzzy upper-bound constraints on risk or financial resources in the first model involves only the abscissas of the two right vertices of the trapezoid (trapezoidal membership function). Meanwhile, the right boundaries of fuzzy covariance matrix values significantly exceed in absolute value the abscissas of the other three vertices of the trapezoid. As a result, artificially large values of auxiliary risk constraints are generated. In the second model, the conversion formula from fuzzy lower-bound constraints on mathematical expectation to crisp constraints uses only the two left vertices of the trapezoid. Consequently, crisp auxiliary constraints on mathematical expectation become artificially small. Moreover, constraints on the use of defuzzification methods for fuzzy risk and budget of the selected project portfolio arise. For instance, the use of the most common defuzzification method (center of gravity) becomes impractical (Mazelis et al., 2016).

It is noteworthy that in our case, the variable values of the models are Gaussian fuzzy numbers, rather than trapezoidal ones. In this regard, an alternative approach is proposed for reducing the given fuzzy optimization problems to crisp ones. Specifically, it is suggested to defuzzify the fuzzy sums in the problems (4) and (5) for each project portfolio (a set of variables y_n), as well as the constraints in the right-hand sides of the inequalities. In this case, defuzzification can be performed, including using the center of gravity method.

4. Results

Let us demonstrate the use of the proposed models using a case study of a large regional university (Vladivostok State University, VVSU). The calculations of fuzzy variable values in the model and the implementation of the optimization procedure are sufficiently complex and labor-intensive. Therefore, a specially designed software suite is utilized.

First and foremost, a causal field of indicators for the development of the university's intellectual capital (IC) is formed, represented as a hierarchical structure (Figure 1). “Quantitative” IC indicators at the lowest-level of IC hierarchy are highlighted in green, while “qualitative” IC indicators are marked in yellow.

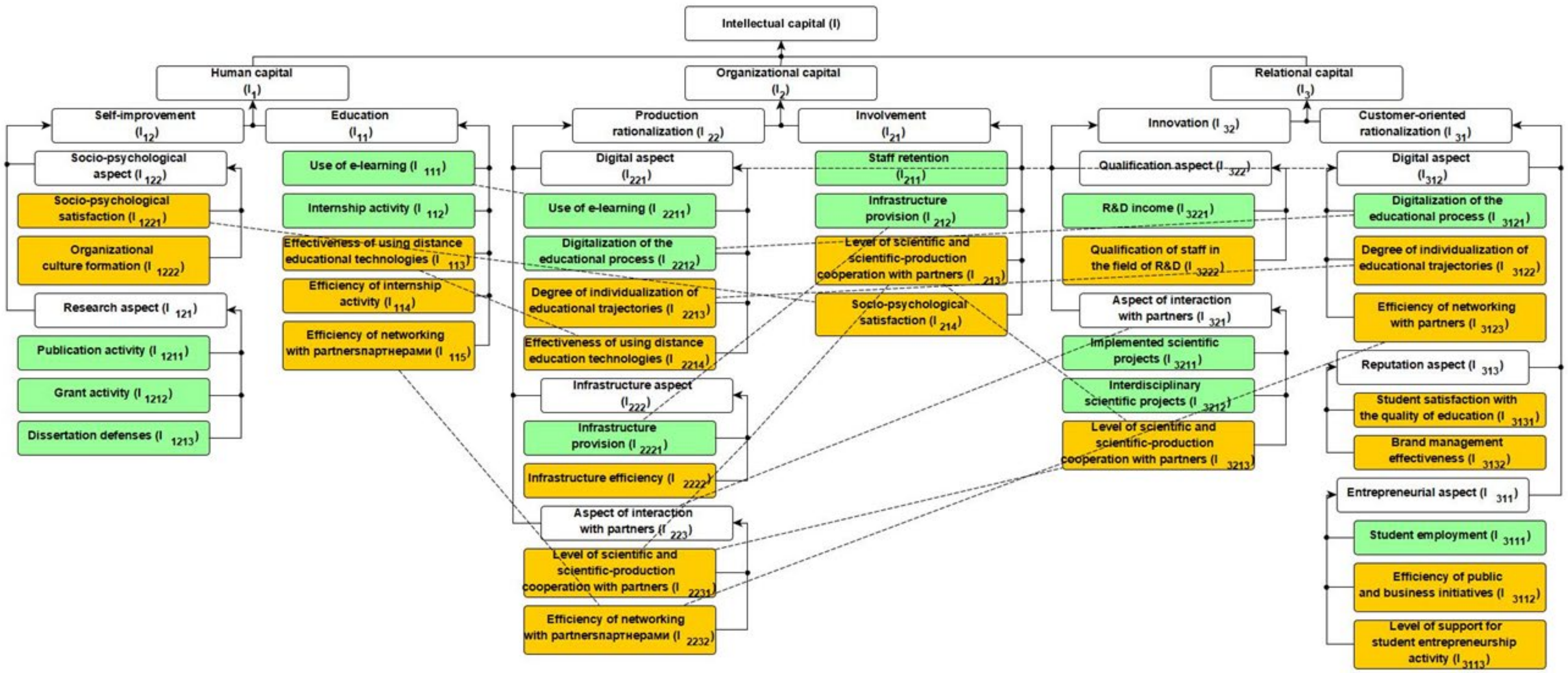

Fig. 1: The Causal Field of IC Development Indicators

In the fuzzy Gaussian type, values of all IC development indicators for the lowest-level of hierarchy for the university are obtained. Subsequently, fuzzy values of all IC development indicators at all levels of the hierarchy are calculated.

To achieve this, bases of fuzzy production rules are formulated. Table 1 presents a fragment of a rule base for the lowest-level of the hierarchy. The values VL, L, M, H, VH correspond to the verbal assessments "Very Low," "Low," "Medium," "High," and "Very High" of the linguistic scale. Each verbal assessment corresponds to a membership function of a fuzzy set. For various variables, these membership functions are different.

Table 1: Fragment of the fuzzy rule base for the indicator “Involvement (I_{21})”

Fuzzy rule number	IF				THEN
	I211	I212	I213	I214	I215
1	VL	VL	VL	VL	VL
2	VL	VL	VL	L	VL
3	VL	VL	VL	M	L
4	VL	VL	VL	H	L
5	VL	VL	VL	VH	L
...	...	...	...	...	...
101	VL	VH	VL	VL	L
102	VL	VH	VL	L	L
103	VL	VH	VL	M	L
104	VL	VH	VL	H	M
105	VL	VH	VL	VH	M
...	...	...	...	...	...
351	M	VH	VL	VL	L
352	M	VH	VL	L	M
353	M	VH	VL	M	M
354	M	VH	VL	H	M
355	M	VH	VL	VH	H
...	...	...	...	...	...
621	VH	VH	VH	VL	M
622	VH	VH	VH	L	H
623	VH	VH	VH	M	H
624	VH	VH	VH	H	VH
625	VH	VH	VH	VH	VH

Let us consider eight strategic activities (projects) aimed at fostering the development of the university's IC (Table 2).

Table 2: Projects for the IC Development at VVSU

Project number	Project name	Project budget (parameters of the approximating Gaussian)

		μ (million rubles)	σ
1	Conducting training for educators in digital educational technologies, including MOOC creation technologies	12.24	1.71
2	Organization of educators' internships at enterprises	5.18	0.82
3	Enhancement of the system of material and non-material rewards and incentives for personnel	20.93	2.32
4	Identification of requests from stakeholders (applicants, parents, students, employers, teaching community) to the university	3.87	0.45
5	Organization of events (business, creative, sports, professional) aimed at team building	4.21	0.74
6	Development of the university's infrastructure component	18.36	2.17
7	Conducting socially oriented and socially significant activities based on the university	6.53	0.98
8	Comprehensive support for the development of scientific activities at the university	20.34	3.19

Furthermore, we consider three scenarios of possible changes in the internal and external environment (conventionally referred to as pessimistic, realistic, and optimistic). Fuzzy probabilities of these scenarios are approximated by Gaussians with the following parameters: for the pessimistic scenario μ=0.2955, σ=0.0318; for the realistic scenario μ=0.5238, σ=0.0497; for the optimistic scenario μ=0.1974, σ=0.0226.

Within the framework of these scenarios, expert assessments in the specified linguistic scale (Table 3) are used to determine the changes in the lowest-level IC development indicators resulting from the implementation of each project.

Table 3: Term-set of the Linguistic Variable "Impact of Project P_i on the indicator e_j"

Linguistic variable value	Trapezoidal membership function
Very weak	<0; 0; 0.01; 0.03>
Weak	<0.02; 0.03; 0.05; 0.07>
Moderate	<0.05; 0.07; 0.10; 0.12>
Strong	<0.10; 0.12; 0.15; 0.20>
Very strong	<0.15; 0.20; 0.25; 0.25>

The weighted average expert responses in the form of Gaussian-type fuzzy numbers are partially provided in Table 4. An empty cell in the table indicates that the implementation of the corresponding project does not lead to changes in that particular indicator. The table includes only those indicators for which the values change as a result of the implementation of two or more projects.

Table 4: Fuzzy Changes in the Lowest-level IC Development Indicators as a Result of Project Implementation within Scenarios (Fragment)

IC indicators / Project numbers	I_{1211}	I_{1221} (I_{214})	I_{211}	I_{3131}	I_{3111}	I_{3112}	I_{3113}
2				(0.241; 0.020) (0.139; 0.024) (0.078; 0.012)			
3	(0.150; 0.023) (0.090; 0.019) (0.035; 0.008)	(0.218; 0.013) (0.152; 0.030) (0.097; 0.011)	(0.220; 0.012) (0.225; 0.043) (0.153; 0.022)				
4				(0.210; 0.043) (0.231; 0.047) (0.121; 0.019)	(0.102; 0.026) (0.025; 0.007) (0.014; 0.006)	(0.153; 0.030) (0.075; 0.011) (0.028; 0.009)	(0.134; 0.040) (0.068; 0.014) (0.032; 0.011)
5		(0.241; 0.018) (0.141; 0.019) (0.081; 0.014)	(0.042; 0.013) (0.021; 0.005) (0.023; 0.006)				

6				(0.147; 0.038) (0.091; 0.015) (0.059; 0.007)		(0.153; 0.018) (0.085; 0.023) (0.050; 0.014)	
7					(0.049; 0.007) (0.010; 0.002) (0.005; 0.001)	(0.227; 0.015) (0.210; 0.023) (0.149; 0.011)	(0.212; 0.048) (0.142; 0.014) (0.065; 0.011)
8	(0.205; 0.027) (0.131; 0.031) (0.073; 0.012)		(0.099; 0.016) (0.023; 0.009) (0.024; 0.008)				

In the framework of fuzzy changes in lowest-level IC development indicators using the Mamdani algorithm, fuzzy changes in IC development indicators at all levels of the hierarchy are calculated as a result of project implementation within scenarios. This includes the calculation of fuzzy changes in the integral IC indicator of the organization, allowing the determination of the fuzzy specific utilities of projects within scenarios, the mathematical expectations of the specific projects' utilities, and the fuzzy elements of the covariance matrix of specific project utilities.

Table 5 presents some results of applying the first model when the university development program is formed based on the criterion of maximizing the expected specific utility while considering program risk constraints and resource volume.

Table 5: Modeling the Formation of the IC Development Program for the University (Maximizing Expected Utility)

Budget constraint, million rubles	Portfolio risk constraint	Numbers of projects included in portfolio	Numbers of projects not included in portfolio	Expected specific utility of portfolio	Expected portfolio budget, million rubles	Portfolio risk
25	0.1	1,2	3,4,5,6,7,8	0.31	17.42	0.0792
	0.25	1,2,7	3,4,5,6,8	0.50	23.95	0.2076
	0.4	2,4,7	1,3,5,6,8	0.61	15.58	0.3613
	0.55	1,2,4,5	3,6,7,8	0.68	25.5	0.4579
	0.7	2,4,5,7	1,3,6,8	0.76	19.79	0.6009
40	0.1	1,6,7	2,3,4,5,8	0.32	37.13	0.0847
	0.25	1,2,7	3,4,5,6,8	0.50	23.95	0.2076
	0.4	1,2,5,7	3,4,6,8	0.64	28.16	0.3957
	0.55	1,2,4,7	3,5,6,8	0.72	27.82	0.455
	0.7	2,4,5,6,7	1,3,8	0.82	38.15	0.6936
55	0.1	2,3,6	1,4,5,7,8	0.33	44.47	0.0998
	0.25	2,3,6,7	1,4,5,8	0.51	51	0.2401
	0.4	1,2,5,7	3,4,6,8	0.64	28.16	0.3957
	0.55	1,2,4,6,7	3,5,8	0.78	46.18	0.5338
	0.7	2,4,5,6,7	1,3,8	0.82	38.15	0.6936
70	0.1	2,3,6	1,4,5,7,8	0.33	44.47	0.0998
	0.25	2,3,6,7	1,4,5,8	0.51	51	0.2401
	0.4	1,2,3,4,6	5,7,8	0.65	60.58	0.3714
	0.55	1,2,4,6,7	3,5,8	0.78	46.18	0.5338
	0.7	1,2,3,4,6,7	5,8	0.83	67.11	0.6118
85	0.1	2,3,6	1,4,5,7,8	0.33	44.47	0.0998
	0.25	2,3,6,7	1,4,5,8	0.51	51	0.2401
	0.4	1,2,3,6,7,8	4,5	0.66	83.58	0.3719
	0.55	1,2,4,6,7	3,5,8	0.78	46.18	0.5338
	0.7	1,2,3,4,6,7,8	5	0.88	87.45	0.6747

Table 6 shows the results of applying the second model, where the university development program is formed according to the criterion of minimum program risk, subject to constraints on resource volume and the expected specific utility.

Table 6: Modeling the Formation of the IC Development Program for the University (Minimizing Risk)

Budget constraint, million rubles	Portfolio risk constraint	Numbers of projects included in portfolio	Numbers of projects not included in portfolio	Expected specific utility of portfolio	Expected portfolio budget, million rubles	Portfolio risk
25	0.15	4	1,2,3,5,6,7,8	0.19	3.87	0.0417
	0.3	4,7	1,2,3,5,6,8	0.37	10.4	0.1448
	0.45	1,4,7	2,3,5,6,8	0.48	22.64	0.1888
	0.6	1,2,4,5	3,6,7,8	0.68	25.5	0.4579
	0.75	It is impossible to form an optimal project portfolio				
	0.9	It is impossible to form an optimal project portfolio				
40	0.15	4	1,2,3,5,6,7,8	0.19	3.87	0.0417
	0.3	1,4,8	2,3,5,6,7	0.34	36.45	0.1085
	0.45	1,4,7	2,3,5,6,8	0.48	22.64	0.1888
	0.6	1,2,5,7	3,4,6,8	0.64	28.16	0.3957
	0.75	2,4,5,7,8	1,3,6	0.81	40.13	0.6832
	0.9	It is impossible to form an optimal project portfolio				
55	0.15	1,3,8	2,4,5,6,7	0.18	53.51	0.024
	0.3	2,3,6	1,4,5,7,8	0.33	44.47	0.0998
	0.45	1,4,7	2,3,5,6,8	0.48	22.64	0.1888
	0.6	1,2,5,7	3,4,6,8	0.64	28.16	0.3957
	0.75	1,2,4,6,7	3,5,8	0.78	46.18	0.5338
	0.9	It is impossible to form an optimal project portfolio				
70	0.15	1,3,8	2,4,5,6,7	0.18	53.51	0.024
	0.3	2,3,6	1,4,5,7,8	0.33	44.47	0.0998
	0.45	1,4,7	2,3,5,6,8	0.48	22.64	0.1888
	0.6	1,2,3,4,8	5,6,7	0.64	62.56	0.36
	0.75	1,2,4,6,7	3,5,8	0.78	46.18	0.5338
	0.9	1,2,4,5,6,7,8	3	0.97	70.73	0.9061
85	0.15	1,3,6	2,4,5,7,8	0.18	51.53	0.024
	0.3	2,3,6	1,4,5,7,8	0.33	44.47	0.0998
	0.45	1,2,3,6,8	4,5,7	0.48	77.05	0.1927
	0.6	1,2,3,4,8	5,6,7	0.64	62.56	0.36
	0.75	1,2,4,6,7	3,5,8	0.78	46.18	0.5338
	0.9	1,2,3,4,5,7,8	6	0.96	73.3	0.8984

5. Discussion

The obtained results allow us to draw the following conclusions.

1. The developed fuzzy models contribute to the instrumental aspect of portfolio optimization theory concerning the development of intellectual capital (IC). These models enable the resolution of the optimization problem for the IC development program as a unified hierarchical system, considering risks. This sets them apart advantageously from existing portfolio optimization models focusing on individual key structural IC components. The distinction of the proposed models from the known project portfolio optimization models for enhancing organizational IC lies in determining fuzzy portfolio utility and risks within a scenario-based approach. The approbation of the models using a specific organization (a large regional university) illustrates their practical applicability.

2. The proposed method for forming an optimal project portfolio for the IC development is universal in the sense that it is applicable to various types of organizations across different industries. Representing IC as a multi-level hierarchical system is universal for the three top levels (integral IC

indicator, key structural components of IC, types of cognitive activities, and the correspondence between types of cognitive activities and structural components of IC). However, the elements of the two lower levels of the hierarchy may vary significantly for different organizations.

3. All the primary stages of the method are standard. However, the fuzzy inference systems used (fuzzy rule bases and fuzzy inference algorithms), as well as defuzzification methods, may vary.

4. Converting fuzzy optimization problems to crisp Boolean quadratic programming problems can be achieved through various methods, each of which has its own advantages and disadvantages. Using Gaussian-type fuzzy numbers as variable values in models mitigates some of the drawbacks associated with trapezoidal fuzzy numbers.

5. The flexibility of the model is determined by the ability to configure a set of the lowest-level IC indicators that align most closely with the specifics of a particular educational organization in its current context, as well as the requirements of the decision-maker. Additionally, there is the option to choose arbitrary membership functions for the fuzzy variables in the model, which are utilized in fuzzy logic systems (sets of fuzzy production rules and fuzzy inference algorithms), as well as defuzzification methods. The advantages of the model are also determined by its orientation towards strategy in forming the causal field of IC development indicators. It allows for the quantitative assessment of "qualitative" IC indicators, considering the expertise levels of professionals in various organizational domains. The model provides the capability for fuzzy evaluation of the financial resources required for project implementation, as well as fuzzy assessment of project utilities within a scenario-based approach and the fuzzy evaluation of risks.

6. In practical application, the model may encounter the following challenges. The absence of a formalized development strategy for the educational organization may hinder the accurate formation of the causal field of IC indicators. On the other hand, addressing the development of IC without aligning it with the overall organizational development strategy is unlikely to be permissible. Calculations for the values of fuzzy variables in the model are sufficiently complex and require appropriate software tools. The challenge of labor-intensive data collection for exogenous variables in the model can be addressed in the following manner. Most values for "quantitative" indicators of the lowest-level IC are typically found within the organization's management accounting system. Obtaining expert assessments for "qualitative" indicators is facilitated by distributing questions among various experts, as well as the software implementation of procedures for conducting expert surveys and processing expert responses.

6. Conclusion

In conclusion, this study proposes fuzzy optimization models for intellectual capital enhancing project portfolio selection under risk considerations. A scenario-based approach is employed for modelling internal and external conditions. The utility of a project is defined as the change in the organization's integral intellectual capital (IC) indicator resulting from project implementation. The measure of risk used is the utility variances. In the first model, the fuzzy objective function is the expected specific utility of the project portfolio, with the level of project portfolio risk and financial resource volume as constraints. In the second model, the fuzzy objective function is the risk of the project portfolio, with expected specific utility and required resource volume as constraints. Constraints in the models are also fuzzy. Fuzzy optimization problems are converted into crisp Boolean quadratic programming problems.

The distinctive feature of the models is the use of fuzzy inference systems in calculating the values of IC development indicators across various hierarchical levels. In this context, the exogenous variables of the models are represented as Gaussian-type fuzzy numbers. This sets the proposed models significantly apart from similar models in which fuzzy variables were of trapezoidal-type fuzzy numbers.

The models are tested using a case study of a large regional university.

The models represent a preliminary conceptual foundation needing substantial future work to realize applied and academic potential. From this initial research, directions such as expanding model diagnostics, comparisons to alternatives, and domain-specific customization can be pursued to build on the base established here.

Further theoretical research in this field may be directed towards developing fuzzy multi-period optimization models for project portfolio development in the context of IC enhancement, accounting for risks. In this regard, blurriness indexes of fuzzy models' variables can be used as a measure of risk. Additionally, utility assessments of projects may involve the use of saturation functions. Moreover, the models may incorporate the effects related to changes in IC indicators influenced by various internal and external factors, regardless of the implementation of certain projects.

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