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Evaluation and ranking of multi-type projects with mixed multi-criteria cost/benefit and optimization of project portfolio selection

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A majority of companies are involved in the planning and execution of projects. The number of projects that companies need to evaluate has significantly increased in recent years. This trend has various causes, such as the digitalization of corporate processes, diversification, or strategic positioning in the face of ever-changing market conditions. The characterization of projects into mandatory and optional, as well as the evaluation of these projects, can be conducted based on various mixed criteria, which may include both cost and benefit criteria. The limited resources of companies necessitate a critical assessment of projects. They must be ranked based on realistic and plausible criteria regarding their benefits and objectives of the company. In the literature, various approaches to project evaluation exist. Examples include financial assessment, the utilization of evaluation models considering risks, or even multi-criteria models that incorporate different aspects of projects into the evaluation process. We propose a robust, scalable, and easily calibrated multi-criteria evaluation model for project evaluation and ranking, encompassing evaluation criteria such as financial criteria measured by Net Present Value (NPV), Risk, Classification, Priority, Strategy, and Sustainability. To achieve this goal, the Technique for Order of Preference by Similarity to Ideal Solution with multi type projects multi mixed cost and benefit criteria (TOPSIS-MTPMMCBC) is employed. The model is adapted to evaluate and rank optional and mandatory projects. An important feature of the projects in this study is that the criteria values of the projects can have negative or positive values. Particularly noteworthy is the increasing significance of sustainability as a key criterion for businesses, driven by political mandates. Consequently, a decision based on the criterion of sustainability will be important in the future and is implemented in the proposed model. The proposed research can be adapted to use a variety of Key Performance Indicators (KPIs) as multiple decision criteria. An objective calculation of the criteria weights for sample dataset was carried out using the CRITIC method, followed by a sensitivity analysis. Subsequently, the optimization of the project portfolio was carried out by combining an integer programming model with the proposed TOPSIS-MTPMMCBC method. An initial solution of project evaluation and ranking is conducted to demonstrate the applications.

1. Introduction

The volume of projects requiring evaluation within companies has been steadily on the rise, as pointed out by Wald et al. (2015). These potential projects often find themselves in direct competition for the allocation of limited corporate resources. It is important for these projects to be selected with a focus on resource efficiency (Adebanjo et al., 2016; Wang et al., 2021). The conception and execution of projects typically assist organizations in successfully maintaining their presence in the market. However, even after projects are implemented, it is often observed that project objectives are not achieved as planned and more deviations are observed (Allen et al., 2014). The consequence of these instabilities is that organizations have to spend more money than planned to achieve the project goals, either partially or fully. Some projects can be initiated due to

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external factors such as legal regulations. Companies must adhere to these regulations in order to avoid potential penalties from governmental authorities. Some of these mandated projects may potentially generate losses for the companies.

Therefore, a careful strategic methodology for evaluation and ranking of projects is important for companies to remain competitive in the market. It is important to select the best projects that align with corporate goals and strategies. One approach to evaluation is Project Portfolio Selection (PPS). This method is known for following long-term corporate goals while utilizing Key Performance Indicators in conjunction with a multi-criteria decision-making method (MCDM) for project evaluation (Ding et al., 2017; Ma et al., 2020; Raval et al., 2022). For successful performance, it is crucial for companies to choose the right decision criteria for conducting PPS. These criteria can be general or tailored to specific industries. As an example, political, geographic, or technical aspects may be relevant. In this research, the focus is on five common decision criteria: Economics, Risk, Priority, Strategy, and Sustainability and one post evaluation criteria: the characterization of the projects into mandatory and optional. This paper aims to develop a robust, scalable, and easily calibratable MCDM model to evaluate projects considering the mentioned criteria.

In this research projects are classified into mandatory and optional projects. This division is important because mandatory projects must be implemented, even if they have negative financial benefits. Mandatory projects can be initiated by external sources, such as new market regulations imposed by the government. In such cases, company processes must comply with regulatory requirements to prevent potential penalties. These projects may have a positive or negative financial return. To date, projects with negative financial returns were given less consideration in the project evaluation process. For the sake of simplicity, we assume in this study that optional projects cannot generate negative financial returns. The characterization of the projects in this study leads to the division of projects into three types: mandatory projects that generate a positive NPV, mandatory projects that generate a negative NPV, and optional projects. Projects with the same characteristics are compared with each other. The characterization of projects into mandatory and optional types is novel and could not be found in the literature by us.

The economic performance of a project is one of the most commonly used criteria in project evaluation. Among these criteria, the Net Present Value (NPV) method is one of the most popular methods for depicting profitability in project evaluation (Remer & Nieto, 1995). In this paper, NPV is utilized as a measure of a project's profitability. Other research that has utilized NPV as an economic indicator in project evaluation is available in Vijayakumar et al. (2022).

A risk criteria is a crucial indicator for the successful evaluation and execution of projects. This criterion is essential for identifying and mitigating instabilities and risks inherent in project implementation, ensuring projects proceed smoothly, and maintaining the company's viability in the market. Significant research studies addressing risk in project evaluation include (Huang et al., 2008; Taylan et al., 2015). While the economic criterion in this study is calculated as the expected NPV, the risk in this study is defined as the standard deviation (statistical value) from expected NPV.

The criterion of priority elucidates the external influences on the company, thereby impacting project evaluation. Among these external influences are changes in customer behavior and preferences, particularly trends in consumption patterns. Additionally, modifications to market regulations by the government, such as changes or adjustments to tax laws, can be of considerable importance. Another critical factor can be the supply chain and logistics, where the availability and reliability of supply chains can play a significant role. In this study, the priority value is calculated as the average value of expert assessments. A more detailed explanation can be found in section 3.

The strategy criterion relates to the internal decision-making influences. The strategic decision shapes the corporate strategy, encompassing market positioning, competitive approaches, and other key factors. Internal influences include efficiency improvements, innovations, internal process optimizations, and other measures to achieve the company's strategic goals. Like the priority value, the strategy value is also given as the average value of the expert evaluations.

Sustainability is increasingly becoming a pivotal criterion for companies, especially as the adverse environmental impacts are being taken seriously by both policymakers and society. Imperatives (1987) defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs."

The three dimensions of sustainability encompass economic, environmental, and social development (Ma et al., 2020). The United Nations (2015) has set long-term goals for sustainable development corresponding to these three dimensions. The European Commision (2019) aims to support these goals at the highest political level and intends to promote them in its external relations to bring about improvements worldwide. This political stance will have direct implications for businesses. Companies may potentially qualify for subsidies to support sustainable development or even face penalties if they engage in unsustainable practices.

To depict environmental impacts, it's crucial to identify the resources used and the resulting emissions. This requires detailed data collection, covering aspects such as production, processing, packaging, transportation, storage, and disposal. European Union (2022) regulation obliges certain companies to report their CO2 emissions. From 2025, large companies will be obliged to submit these reports. Reporting on CO2 emissions can therefore play an important role in decision-making and the implementation of projects. In this context, it is important to integrate the criterion of sustainability into the decision-making process. This process aims to establish the environmental footprint of a company. In this study, it is utilized to integrate the environmental aspect of sustainability into project evaluation.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is a solution approach that addresses the described problem. In the Technique for Order of Preference by Similarity to Ideal Solution with multi cost and benefit criteria and mixed values (TOPSIS-MTPMMCBC) extension, we distinguish between two types of criteria: cost criteria and benefit criteria. For a benefit criterion, the maximum value is selected for the Positive Ideal Solution (PIS), while the minimum value is chosen for the Negative Ideal Solution (NIS). In our analysis the economic criterion, the priority criterion and the strategy criterion are benefit criteria, with the higher the value, the more desirable. For the cost criterion, the minimum value is assigned to the PIS and the maximum value to the NIS. The risk criterion and the sustainability criterion are cost criteria, and the lower the value, the more desirable. This extension can handle cost and benefit criteria that can have both positive and negative values like NPV. As described, mandatory projects can generate either negative or positive financial returns. Likewise some projects can generate positive emissions, while others may produce negative emissions. Negative emissions include methods such as Direct Air Capture, which removes CO2 from the atmosphere.

One advantage of the TOPSIS method is that a sensitivity analysis can be conducted. In this study, the sensitivity analysis is performed by varying the weights of the criteria, allowing us to describe the sensitivity of each individual criterion. A sample dataset is created to test the model and sensitivity analysis is performed.

A logical next step is the selection of optimal project portfolios. Since corporate resources are limited and not all projects can be implemented, the selection of optimal portfolios is crucial. This selection can be carried out using Integer Programming models. In this context, the TOPSIS model proposed in this paper is integrated into the Integer Programming model to calculate optimal project portfolios. Integer programming approaches for project portfolio selection have been applied by Tavana et al. (2015), Eckhause et al. (2012), and Wang & Hwang (2007).

This paper is structured as follows. In the second section, a detailed literature review is presented and the present work is classified in the literature. In section three, we present the TOPSIS-MTPMMCBC model and explain all evaluation criteria. In the following section, we provide an initial solution for a sample of test projects. We perform sensitivity analysis of the model in section five. In Section Six, we performed a project portfolio selection and conducted a sensitivity analysis on the results. In the final section, we interpret and discuss the results and provide an outlook for future research.

2. Literature review

In recent years, researchers have increasingly focused on the assessment and evaluation of projects. In its simplest case, project evaluations were made based on the amount of financial return.

It quickly became clear that a decision based on a single criteria would not be optimal for project evaluation. Since financial returns are uncertain, researchers have studied decision making under risk. Von Neumann & Morgenstern (1947) published the Expected Utility Theory where they presented four axioms (completeness, transitivity, continuity, and independence) for rational decision making under risk. The authors formulated the uncertainties as objective probabilities. Other papers in the field of decision-making under risk include the works of Quigging (1982), Fishburn (1990), Schmidt (2001), Abdellaoui (2002) and Laury & Holt (2005).

One of the most popular methods for project evaluation is MDCM, in which multiple criteria are simultaneously taken into account, such as in the work by Yu et al. (2012). In Fig. 1, a selection of MDCM methods is presented.

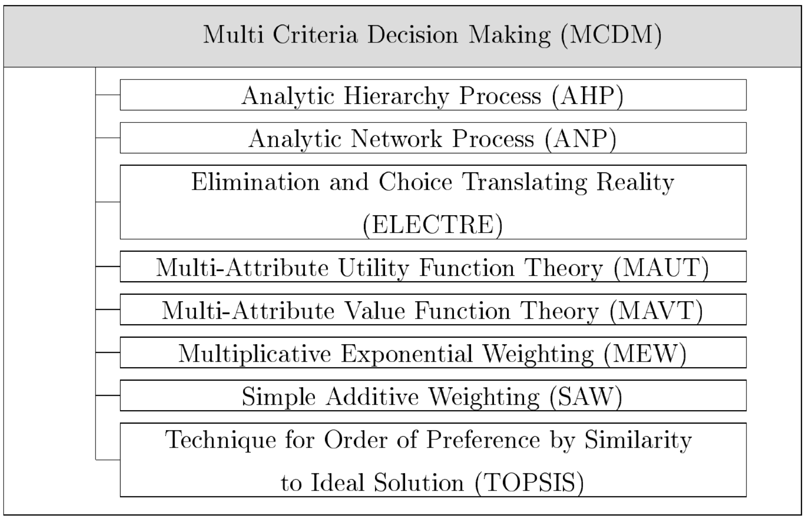

Fig. 1. Multi Criteria Decision Making Methods

Jeng and Huang (2015) use a hybrid MCDM method to evaluate project portfolios. This hybrid method consists of a modified Delphi method, a decision-making trial and evaluation laboratory method, and an ANP. The authors propose a 4-Dimensional model called Need-Solution-Benefit- Differentiation (NSBD), which considers product and service differentiation. First, criteria are identified for each dimension, and then the relationships between the factors are analyzed, including the relation map among portfolio evaluation dimensions and the criteria.

Demircan Keskin (2020) proposed a fuzzy analytic network process (FANP) and analyzed the main criteria for evaluating Industry 4.0 projects, including organizational, financial, technical, risk, and productivity improvement criteria, as well as subcriteria. The author calculated the importance levels of these criteria by considering their interdependencies relationships, using pairwise comparison matrices.

Tavana et al. (2019) proposed a hybrid model that combines Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy Inference System (FIS) for project evaluation. This model considers both qualitative and quantitative criteria and aims to achieve two objectives: maximizing project benefits and minimizing project risks. The FAHP is used to weight the subcriteria, and then the score for each project and subcriterion is evaluated using FIS. The final score for each project is calculated by summing up the weighted subcriteria scores and the evaluated value for the project.

Wu et al. (2018) proposed a fuzzy multi-attribute decision making and fuzzy multi-objective programming method for project evaluation. The authors considered 10 decision attributes categorized into resource conditions, economics, risk, and sustainability. They constructed a decision matrix and divided the evaluation attributes into quantitative attributes with precise measurement and imprecise measurement, for which decision makers used triangular intuitionistic fuzzy numbers (TIFNs) to reflect uncertainties and qualitative attributes. The weights of the attributes were calculated using AHP. After calculating the net flows, a sensitivity analysis was performed to eliminate inferior alternatives. Alternatives with flow values that were always lower than the defined critical point were eliminated.

Zhang et al. (2020) consider the historical performance of projects and apply fuzzy mathematics for their evaluation. First, they select evaluation criteria and weight them using a pairwise comparison matrix with fuzzy linguistic variables to ensure consistency. The criteria weights are then incorporated into an extended vlsekriterijuska optimizacija i komoromisno resenje (EVIKOR, translated: Extended Multicriteria Optimization and Compromise Solution) model to evaluate project performance while taking into account historical performances. In their study, they consider economic influencing factors that can be estimated through mathematical models and simulations such as the Monte Carlo simulation. The researchers then compare the second phase with two methods of the extended TOPSIS and fuzzy AHP.

Ranjbar et al. (2022) analyze multiple modes for project implementation and calculate the net present value (NPV) of each mode. To evaluate the projects, they select four qualitative criteria Technical risk, Political and social risk, Strategic adaptation and Competitive advantage, estimate weights for each criterion, and apply fuzzy TOPSIS. In the next step, they propose fuzzy mathematics to maximize the NPV of profit and the portfolio score.

Abdel-Basset et al. (2019) presents a method that integrates the TOPSIS into the Decision-Making Trial and Evaluation Laboratory (DEMATEL) under a neutrosophic environment. The criteria for MCDM are assessed based on expert opinions, which can sometimes be unreliable due to the non-deterministic environment. To handle and overcome the ambiguity or lack of confirmation of information, the authors employ neutrosophic set theory. Ten criteria (investment, rate of return, risk, expected profit, payback period, similarity to existing businesses, expected lifespan, flexibility, environmental impact, and competition) are divided into tangible criteria, which are measurable, and intangible criteria, which are non-measurable.

Amiri (2010) presents a project selection method for oil-fields development utilizing the Analytic Hierarchy Process (AHP) and fuzzy TOPSIS methods. AHP is employed to analyze the structure of the project selection problem and determine the weights of the criteria, while the fuzzy TOPSIS method is utilized to obtain the final ranking. The criteria considered include Size/Complexity, Reasonableness of Cost Estimates, Scope Adequacy/Level of Detail, Duration, Technology, and Location.

Tavana et al. (2015) propose a fuzzy hybrid project portfolio selection method incorporating Data Envelopment Analysis (DEA), TOPSIS, and Integer Programming (IP). The selection process is divided into three stages: preparation, evaluation, and selection. In the preparation stage, DEA is utilized for an initial screening. During this stage, decision makers' objectives, priorities, initial constraints, thresholds, and evaluation criteria are identified. In the evaluation stage, TOPSIS is applied for ranking the projects. This stage involves several steps to assess the projects based on the identified criteria. The final stage, selection, involves linear Integer Programming (IP) to select the most suitable project portfolio. IP is employed akin to a knapsack problem with multiple constraints to optimize the selection process.

Mahmoudi et al. (2021) investigates large-scale MCDM in the presence of missing values, focusing on project selection utilizing TOPSIS OPA (Ordinal Priority Approach). That study employs incomplete big data for decision-making. The criteria are first clustered using Principal Component Analysis (PCA) and the K-means algorithm to cluster the alternatives and estimate the optimal clusters. These clusters are then ranked using the Fuzzy TOPSIS (TOPSIS-F) and the Ordinal Priority Approach (OPA). The criteria considered in the analysis include:Time (Project Duration and Project Delay), Number of items in each Project, Score of the client, Physical weight, Design status (Revision number and Code number), Level of difficulty.

Taylan et al. (2014) identify key risk criteria in their study and assess the overall risk of the studied projects using a hybrid method: Firstly, the Relative Importance Index (RII) method is employed to prioritize project risks based on data collected via survey. Next, projects are categorized using the Fuzzy Analytic Hierarchy Process (FAHP) and TOPSIS-F methodologies. FAHP is utilized to assign favorable weights to the fuzzy linguistic variable of overall project risk. Fuzzy TOPSIS is emphasized as particularly suitable for solving group decision-making problems in a fuzzy environment.

To improve project evaluation, researchers have considered more and different criteria. Heidenberger and Stummer (1999) and Iamratanakul et al. (2008) have provided a good overview of the various project portfolio selection methods, including project evaluation. In none of the mentioned studies could a study be found that presented both negative and positive criteria values for the same project criterion. Additionally, we were unable to find a distinction between mandatory and optional projects.

3. Model approach and methodology

In this section, a project evaluation and ranking framework is presented. Fig. 2 shows that the number of criteria k and the associated weightings of the criteria must first be determined. This figure shows that the criteria can be subdivided into sub-criteria. Demonstrating that the proposed model can be easily extended. Both in the number of criteria k and in the subdivision of the criteria into subcriteria.

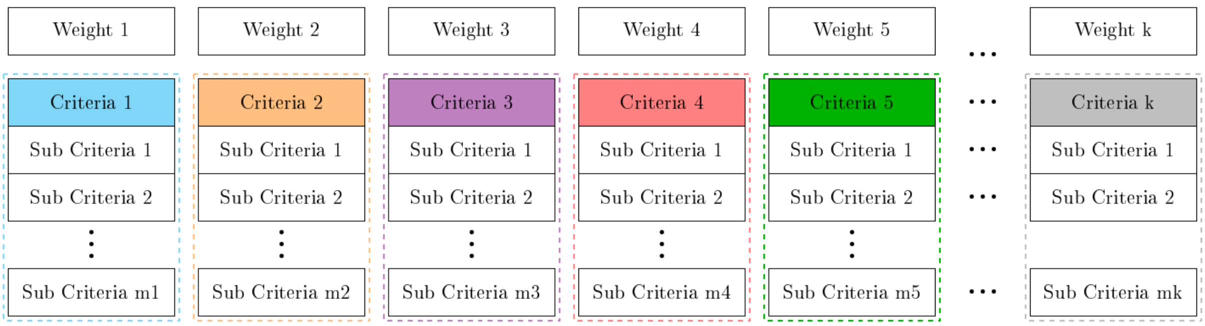

Fig. 2. Definition of criteria and weightings

For the sake of simplicity, we limit our analysis to five criteria: Economics, Risk, Priority, Strategy, and Sustainability. Furthermore, we will treat these criteria as a single entity, omitting any subcriteria that may exist under each criterion. Finally, we assume for the sake of simplicity that the criteria are independent of one another. Project Economics is calculated using the expected NPV approach. The measurement of project risk is given by the standard deviation of the expected NPV. The priority criterion and the strategy criterion are given an average value assessed by the decision-makers. The Sustainability Criteria is measured in kilograms of CO2. Fig. 3 illustrates the potential projects and the evaluation criteria used to evaluate and prioritize the projects in a TOPSIS-MTPMMCBC framework.

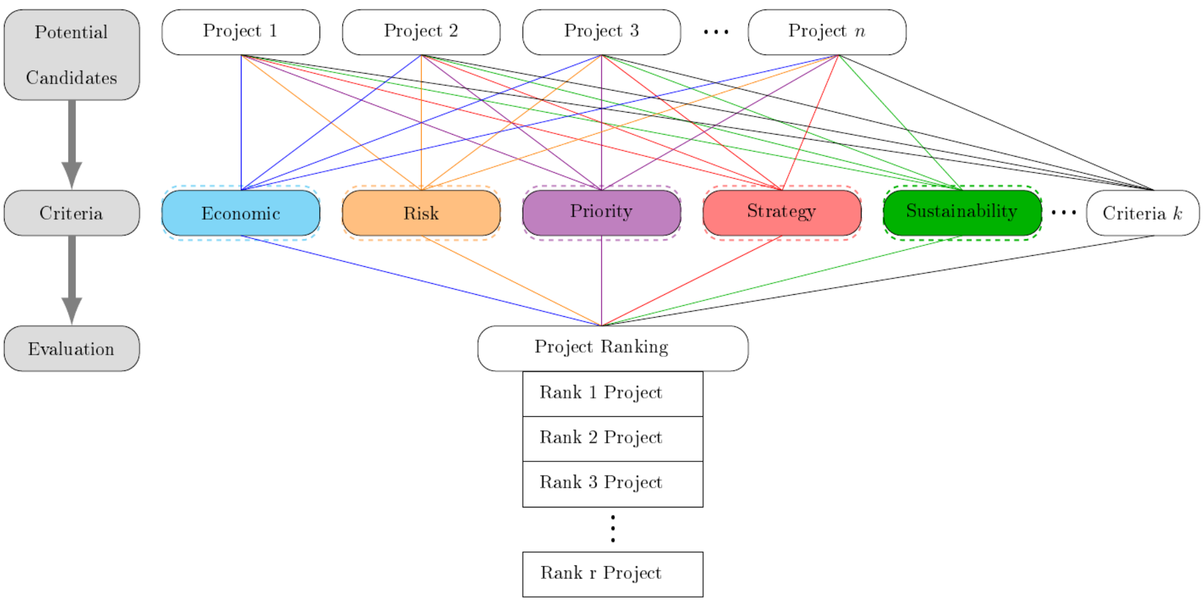

Fig. 3. Strategic Project Evaluation and Ranking

Table 1
Summary of studies using different evaluation criteria

Author	Method	Classification	Economic	Risk	Priority	Strategy	Sustainability	Case Study
Liu & Wei, 2018	Fuzzy TOPSIS			✓				Electric Vehicle Charging Location
Ma et al., 2020	Modified Fuzzy TOPSIS		✓				✓	Paper Manifacturing
Solangi et al., 2018	AHP Fuzzy TOPSIS		✓			✓	✓	Wind power location
Taylan et al., 2014	Fuzzy AHP Fuzzy TOPSIS			✓				Construction Sector
Proposed Approach	TOPSIS-MTPMMCBC	✓	✓	✓	✓	✓	✓	General

Table 1 shows a selection of studies and the criteria used in these MCDM problems. Note Liu and Wei (2018) consider various risk criteria such as economic risk and enviromental risk.

3.1 Project Characteristics and Types - Mandatory and optional projects

In this paper, projects are divided according to their characteristics whether they are mandatory or optional.

The set P comprises all project proposals p_j.

$$\boldsymbol{p_1, p_2, \ldots, p_j \in P} \tag{1}$$

Next the classification variable c of Project j is introduced.

$$\boldsymbol{c_j} = \begin{cases} \boldsymbol{man} & \textbf{If project is mandatory} \\ \boldsymbol{opt} & \textbf{If project is optional} \end{cases} \tag{2}$$

Consequently, the projects are divided into two subsets: the set of mandatory projects P_{man} and the set of optional projects P_{opt}. A project cannot be contained in both sets at the same time. The division of projects into the two subsets is crucial. Even if mandatory projects have to be carried out, it is important from a business perspective to evaluate and prioritize them, as these projects also require resources. This is particularly important both for project portfolio selection and it is important if sequence optimization of activities associated with these project is to be scheduled. The set of mandatory projects includes two types: projects that generate a positive NPV and projects that generate a negative NPV. Optional projects represent a third type and consist solely of projects that generate a positive NPV. Mandatory projects inherently take preference over the projects in the set of optional projects. The evaluation of the projects is conducted in one set, but the ranking is carried out separately for both subsets mandatory and optional.

3.2 Project Economics

Projects are typically evaluated based on their performance throughout their entire impact period. The future revenues and expenses of the project are accumulated over time t and discounted to their present value. This calculation is commonly referred to as the NPV.

The economic value E_t at time t is determined by the summation of cash inflows I_t and outflows O_t at that specific time and can be expressed by the equation

$$\boldsymbol{E_{jt} = I_{jt} - O_{jt},} \quad \textbf{with } \boldsymbol{t \geq 1} \tag{3}$$

For time t, O_t encompasses the summation of diverse costs, including material costs, energy costs, maintenance costs, and other cost categories. I_t captures the financial returns obtained at time t.

When the economic values are discounted to the current time using the discount rate i and summed, the result is the NPV for the project investment:

$$\boldsymbol{NPV_j = \sum_{t=0}^{T_j} \frac{E_{jt}}{(1+i)^t}} \tag{4}$$

Initially designed for valuing bonds, the NPV method was later applied to evaluate investment opportunities in real projects (Espinoza & Morris, 2013). The NPV considers risk and uncertanty such as fluctuatuons in demand and price (Ma et al., 2020). Ultimately, the NPV provides a reliable economic measure for evaluating investments in projects.

3.3 Project Risk measure

Although the NPV is an effective method for financial evaluation of projects, determining the NPV is associated with uncertainties. Equation (4) includes uncertain variables such as E_{jt}. To calculate the investment return, the expected value is utilized, which is determined through Equation (5). μ_j represents the expected value of project j.

$$\mu_j = E\left(\sum_{t=0}^{T_j} \frac{E_{jt}}{(1+i)^t}\right) \tag{5}$$

Since the true value of the investment is unknown, the variance is introduced into the model to measure investment risk. The investment risk measure is expressed as the standard deviation to capture the extent of fluctuations in financial returns. Eq. (6) can be used to calculate the variance, and subsequently, Equation (7) is employed to determine the standard deviation.

$$\sigma_j^2 = Var\left(\sum_{t=0}^{T_j} \frac{E_{jt}}{(1+i)^t}\right) \tag{6}$$

$$\sigma_j = \sqrt{\sigma_j^2} \tag{7}$$

3.4 Priority Criteria

External influences are intended to be incorporated into the evaluation process through the use of priority criteria. External factors include market changes, which can be driven by customer demands or regulatory adjustments, among other things. The priority class value in this study is considered to be a average value determined by experts and decision-makers. The experts and decision-makers evaluate the priority criterion based on ordinal priority classes. Table 2 provides the linguistic translation of these classes. From these evaluation, an average value is calculated for each project, which is represented as a real number.

Table 2
Linguistic Term of Priority Class

Priority Class Value	Linguistic Term
1	Very Low Priority
2	Low Priority
3	Medium Priority
4	High Priority
5	Very High Priority

3.5 Strategy Criteria

In this research, a focus is placed on examining how the strategic orientation of the project influences its environment and consequently impacts the corporate strategy. Thus, this criterion focuses on internal decision influences. Internal influences include efficiency improvements, innovations, internal process optimizations, and other measures to achieve the company's strategic goals.

Similar to the priority criterion, the experts and decision-makers evaluate the strategy criterion based on ordinal strategy level. Table 3 provides the linguistic translation of these level. Consequently, an average value is calculated from these experts evaluations for each project.

Table 3
Linguistic Term of Strategy Level

Strategy Level Value	Linguistic Term
1	Very Low Strategy level
2	Low Strategy level
3	Medium Strategy level
4	High Strategy level
5	Very High Strategy level

3.6 Sustainability Criteria

The United Nations (2005) categorized sustainability into three key dimensions: economic, environmental, and social. For the current purpose the economic aspect may falls under the criterion of 'Economics' (NPV). As a result in this context for sake of simplicity, this research focuses on the Environmental aspects initially.

Environmental Sustainability describes the imperative to preserve and protect natural resources and ecosystems over the long term, ensuring the fulfilment of the needs of both current and future generations while minimizing environmental impact (Imperatives, 1987).

The measurement of the environmental aspect can be measured in kilograms of CO2.

3.7 The proposed adapted TOPSIS-MTPMMCBC approach

TOPSIS is one of the classic methods used in Multi-Criteria Decision Making. For the criteria, we differentiate between two types: cost criteria and benefit criteria. For a benefit criterion, the maximum value is selected for the positive ideal solution (PIS), while the minimum value is chosen for the negative ideal solution (NIS). Conversely, for a cost criterion, the minimum value is assigned to the PIS and the maximum value to the NIS.

The TOPSIS-MTPMMCBC method is conducted as follows:

Step 1 - Defining the input matrix

Let $p_{j,c}$ denote project j with characterization c as per Eq. (2). Then, the set of all projects is $P = p_{1,c}, p_{2,c}, \dots, p_{n,c}$. Here, n represents the total number of possible alternatives. Within the set of all alternatives, n_1 alternatives are mandatory projects, and they belong to the set of all mandatory projects $P_{man} = p_{1,man}, p_{2,man}, \dots, p_{n_1,man}$. Consequently, n_2 alternatives are optional projects and belong to the set of optional projects $P_{opt} = p_{1,opt}, p_{2,opt}, \dots, p_{n_2,opt}$. It holds that $n_1, n_2 \in n_a$. The criteria are $CR_k (k = 1, \dots, m)$, with the performance ratings $x_{j,c,k}$. The input matrix is:

	CR_1	CR_2		CR_m
$p_{1,man}$	$x_{1,man,1}$	$x_{1,man,2}$	$\cdots$	$x_{1,man,m}$
$p_{2,man}$	$x_{2,man,1}$	$x_{2,man,2}$	$\cdots$	$x_{2,man,m}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$p_{n_1,man}$	$x_{n_1,man,1}$	$x_{n_1,man,2}$	$\cdots$	$x_{n_1,man,m}$
$p_{1,opt}$	$x_{1,opt,1}$	$x_{1,opt,2}$	$\cdots$	$x_{1,opt,m}$
$p_{2,opt}$	$x_{2,opt,1}$	$x_{2,opt,2}$	$\cdots$	$x_{2,opt,m}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$p_{n_2,opt}$	$x_{n_2,opt,1}$	$x_{n_2,opt,2}$	$\cdots$	$x_{n_2,opt,m}$

Step 2 - Normalize the input matrices.

In this step, performance ratings are normalized to ensure comparability among criteria measured with different units or scales (Eq. (8)).

$$r_{j,c,k} = \frac{x_{j,c,k}}{\sqrt{\sum_{l=1}^{n_a} x_{l,c,k}^2}} \quad (8)$$

$x_{j,c,k}$, represents project j's with project characteristic c and evaluation regarding criterion k.

Step 3 - Adding the criteria weights to the decision matrix.

The weighted values $v_{j,c,k}$, are calculated using Eq. (9).

$$v_{j,c,k} = w_k * r_{j,c,k} \quad (9)$$

where w_k is the weight for criteria k.

Step 4 - Determine the Positive Ideal Solution PIS $v_{c,k}^+$ and Negative Ideal Solution NIS $v_{c,k}^-$

The PIS and the NIS for benefit criteria are determined as follows

$$v_{c,k}^+ = max\{v_{1,c,k}, v_{2,c,k}, \dots, v_{n_a,c,k}\} \quad (10)$$

$$v_{c,k}^- = min\{v_{1,c,k}, v_{2,c,k}, \dots, v_{n_a,c,k}\} \quad (11)$$

PIS and NIS for cost criteria:

$$v_{c,k}^+ = min\{v_{1,c,k}, v_{2,c,k}, \dots, v_{n_a,c,k}\} \quad (12)$$

$$v^{-}_{c,k} = max\{v_{1,c,k}, v_{2,c,k}, \dots, v_{n_a,c,k}\} \quad (13)$$

Step 5 - Calculate the distance for each project to PIS and NIS.

Eq. (14) is used to calculate the distance $D^{+}_{j,c}$ of the project value to the PIS and Equation 15 the distance $D^{-}_{j,c}$ to the NIS.

$$D^{+}_{j,c} = \sqrt{\sum_{k=1}^{n_a} (v^{+}_{c,k} - v_{j,c,k})^2} \quad (14)$$

$$D^{-}_{j,c} = \sqrt{\sum_{k=1}^{n_a} (v^{-}_{c,k} - v_{j,c,k})^2} \quad (15)$$

Step 6 - Calculation of the proximity coefficients CS to the ideal solution for each alternative project.

$$CS_{j,c} = \frac{D^{-}_{j,c}}{D^{-}_{j,c} + D^{+}_{j,c}} \quad (16)$$

Step 7 - Ranking of the alternative projects based on the proximity coefficients $CS_{j,c}$.

In this step, the projects are ranked from largest to smallest based on their proximity coefficients. The project with the highest value is considered the best choice.

3.7.1 CRITIC weight method to calculate weight for initial solution

An initial solution can utilize any initial weighting values provided they sum to 1. However, an objective determination of the weights based on the available information derived from the ratings is a more preferred method for weight determination such as the CRITIC method. This method is used in research studies such as Saxena et al. (2022) and Xu et al. (2020). The main idea is to determine the weights based on two indicators: Volatility (relative strength) and conflict (correlation). Volatility is calculated using the standard deviations of the criteria. This means that the standard deviation for each criterion is calculated. The higher the standard deviation, the higher the volatility and consequently the higher the weighting. The conflict is calculated using the correlation coefficient between the criterias. If this value is larger between the criteria, the conflict between these criteria is lower and therefore the weighting is lower.

Normalized decision matrix values of the j-th alternative of the k-th criterion are calculated by

$$q_{j,k} = \frac{x_{j,k} - min(x_k)}{max(x_k) - min(x_k)} \quad (17)$$

for benefit criteria and

$$q_{j,k} = \frac{max(x_k) - x_{j,k}}{max(x_k) - min(x_k)} \quad (18)$$

for cost criteria. The volatility of the criteria is expressed as standard deviation ST and can calculate by the expected Value $\overline{q}$ of the normalized values.

$$\overline{q}_k = \frac{1}{n}\sum_{l=1}^{n} q_{l,k} \quad (19)$$

$$ST_k = \sqrt{\frac{\sum_{l=1}^{n}(q_{l,k} - \overline{q}_k)^2}{n-1}} \quad (20)$$

The Conflict between the criteria k_1 and k_2 is expressed as correlation coefficient and is calculated by Equation 21.

$$\rho_{k_1,k_2} = \frac{\sum_{l=1}^{n}(q_{l,k_1} - \overline{q}_{k_1})(q_{l,k_2} - \overline{q}_{k_2})}{\sqrt{\sum_{l=1}^{n}(q_{l,k_1} - \overline{q}_{k_1})^2 \sum_{l}^{n}(q_{l,k_2} - \overline{q}_{k_2})^2}} \quad (21)$$

Calculation for weights w_k of each ranking criteria is obtained using Eq. (22).

$$QI_k = ST_k \sum_{l=1}^{m} (1 - \rho_{k,l}) \tag{22}$$

where QI_k is the quantity of information contained in k-th criteria. The weight of each criterion is

$$w_k = \frac{QI_k}{\sum_{l=1}^{m} QI_l} \tag{23}$$

The weight value range is between 0 and 1. The sum of the weights equals 1.

3.8 Integer Programming Model for Project Portfolio Selection

After the evaluation and ranking phase, project portfolios can be determined. The goal of portfolio determination is to invest the company's resources in projects that will provide the optimal project portfolio. In this process, resources are not directly allocated to the projects with the highest scores Tavana et al. (2015).

We propose an integer programming model for project portfolio selection.

Let z be the objective function to be maximized,

$$max\ z = \sum_{l=1}^{n_1} CS_{l,c=1} x_{l,c=1} + \sum_{h=1}^{n_2} CS_{h,c=0} x_{h,c=0} \tag{24}$$

$CS_{j,c}$ is the proximity coefficient of the l-th or h-th project with the characteristic $c = 1$ mandatory project or $c = 0$ optional project, n_1 number of mandatory projects, n_2 number of optional projects.

Constraint 1 - Implementation of projects

The first constraint concerns whether projects are included in the project portfolio or not implemented. For simplicity, it is assumed that mandatory projects are always included in the portfolio. This constraint ensures that mandatory projects must be executed.

It is valid for

(1) Mandatory projects

$$x_{n_1,c=1} = 1 \tag{25}$$

(2) Optional projects

$$x_{n_2,c=0} \leq 1 \tag{26}$$

Constraint 2 - Resource allocation

The second constraint concerns resource allocation. The required resource effort is given in mandays and denoted as $S_{b,n_a,c}$, where b represents the respective resource skill. n_a refers to project a, which can be either mandatory or optional. TS_b represents the total number of available company resources for skill b, given in mandays.

$$\sum_{l=1}^{n_1} S_{b,l,c=1} x_{l,c=1} + \sum_{h=1}^{n_2} S_{b,h,c=0} x_{h,c=0} \leq TS_b \tag{27}$$

Constraint 3 - Sustainability Limit

$$\sum_{l=1}^{n_1} SUS_{l,c=1} x_{l,c=1} + \sum_{h=1}^{n_2} SUS_{h,c=0} x_{h,c=0} \leq SLMT \tag{28}$$

The CO2 emissions of the projects are given in $SUS_{n_a,c}$ and $SLMT$ is the upper Limit of CO2 emissions for the Company.

Constraint 4 - Non negativity condition

$$x_{1,1}, x_{2,1}, \dots, x_{n_1,1}, x_{1,0}, x_{2,0}, \dots, x_{n_2,0} \geq 0 \tag{29}$$

Constraint 5 - Integer Value

The variable $x_{n_a,c}$ can only take integer values of 0 or 1.

$$x_{n_a,c} \in \{0, 1\} \quad (30)$$

The variable TS_b represents the total amount of resources with skill b, and is defined as the product of the number of resource packages and the size of each package:

$$TS_b = nrp_b \times srp_b \quad (31)$$

Similarly, the variable $SLMT$ is defined as the product of the number of emission limit packages and the fixed size of each package:

$$SLMT = nep \times sep \quad (32)$$

where nep is the number of emission limit packages, and sep is the size of each package.

4. Example of multi type project evaluation with cost/benefit criteria and mixed value

In this example, project evaluation and ranking are performed based on 15 sample projects P1-P10. Projects P1, P4, P6, P8 and P9 are mandatory projects. Projects P2, P3, P5, P7, P10, P11, P12, P13, P14 and P15 are optional projects. As described in the previous chapter, the evaluation criteria are Economic, Risk, Priority, Strategy and Sustainability. The criteria values for the projects are shown in Table 4.

Table 4
Example Projects for Evaluation and Ranking

Project	Characteristic	Economic NPV (in €)	Risk measure (in €)	Priority	Strategy	Sustainability CO2 in KG
P1	man	16300	7600	3.6	3.1	13000
P2	opt	6000	600	3.9	3.4	-4500
P3	opt	25000	9800	3.1	4.1	19000
P4	man	-14000	5300	4.2	3.9	10000
P5	opt	2500	1500	4.1	2.9	6000
P6	man	-5000	1500	3.8	3.2	10000
P7	opt	4000	400	2.8	3.5	15000
P8	man	12000	1200	3.9	3.8	15000
P9	man	-2000	800	4.1	4.1	-2000
P10	opt	4500	900	3.3	3.7	12000
P11	opt	1000	100	2.6	2.8	-1000
P12	opt	5000	300	3.6	3.5	4000
P13	opt	12000	3000	3.7	3.8	5000
P14	opt	6800	1100	4.1	4.2	1000
P15	opt	2000	100	2.8	3.3	-500

The criteria weights applying the CRITIC method are shown in Table 5.

Table 5
Criteria weights (calculated by CRITIC Method)

w_1 (Economic)	w_2 (Risk)	w_3 (Priority)	w_4 (Strategy)	w_5 (Sustainability)
0.190	0.209	0.207	0.200	0.193

Table 6 shows the distance of the projects to the PIS and NIS results calculated using the TOPSIS method, the values of the proximity coefficients of all projects and the Rankings in the subsets mandatory and optional.

Table 6
PIS, NIS, proximity coefficients and rankings of all projects

Projects	$D_{j,c}^{+}$	$D_{j,c}^{-}$	$CS_{j,c}$	Ranking in Subset
P1	0.149	0.154	0.507	3 – (Mandatory)
P2	0.093	0.206	0.690	1 – (Optional)
P3	0.188	0.189	0.502	10 – (Optional)
P4	0.216	0.086	0.284	5 – (Mandatory)
P5	0.124	0.162	0.566	7 – (Optional)
P6	0.165	0.139	0.458	4 – (Mandatory)
P7	0.144	0.165	0.535	9 – (Optional)
P8	0.119	0.181	0.604	1 – (Mandatory)
P9	0.131	0.183	0.582	2 – (Mandatory)
P10	0.131	0.164	0.555	8 – (Optional)
P11	0.121	0.190	0.611	6 – (Optional)
P12	0.107	0.185	0.634	4 – (Optional)
P13	0.091	0.177	0.662	3 – (Optional)
P14	0.093	0.190	0.670	2 – (Optional)

P15	0.150	0.195	0.623	5 – (Optional)

5. Sensitivity analysis

Sensitivity analysis is conducted to examine the effects of criteria weighting on the ranking of the projects. To illustrate the robustness of the proposed MCDM method in a straightforward manner, simple experimental examples are deliberately used. The analysis is carried out by varying the weights and applying the TOPSIS method to determine the revised rankings. Research studies in which sensitivity analyses based on varying the weights were carried out in a similar way are Roy & Patro (2021), Kumar et al. (2018), Ma et al. (2020) and Dhara et al. (2022). In an initial sensitivity analysis, seven different Frameworks are considered, as shown in Table 7.

Table 7
Variation of the weights on different Frameworks

Criteria	FW 1 CRITIC	FW 2 Equal	FW 3 Economic	FW 4 Risk	FW 5 Priority	FW 6 Strategy	FW 7 Sustainability
Economic	0.190	0.2	0.5	0.125	0.125	0.125	0.125
Risk	0.209	0.2	0.125	0.5	0.125	0.125	0.125
Priority	0.208	0.2	0.125	0.125	0.5	0.125	0.125
Strategy	0.200	0.2	0.125	0.125	0.125	0.5	0.125
Sustainability	0.193	0.2	0.125	0.125	0.125	0.125	0.5

In Framework 1, the weights were calculated using the CRITIC method. In Framework 2, all weights were set equally. In the remaining Frameworks, one criterion was set to a high value (50%) while all other criteria were set to an equal value (12.5%). Table 8 presents the proximity coefficients $CS_{j,c}$ of optional projects and the rankings for all Framework.

Table 8
Proximity Coefficients Values and rankings of optional projects on different Frameworks

Project	FW 1 CRITIC	FW 2 Equal W.	FW 3 Economic	FW 4 Risk	FW 5 Priority	FW 6 Strategy	FW 7 Sustainability
P2	0.690 (1)	0.681 (1)	0.535 (4)	0.844 (1)	0.690 (1)	0.663 (3)	0.844 (1)
P3	0.502 (10)	0.517 (10)	0.810 (1)	0.261 (10)	0.506 (9)	0.532 (8)	0.278 (10)
P5	0.566 (7)	0.554 (7)	0.440 (8)	0.762 (8)	0.583 (5)	0.520 (9)	0.553 (7)
P7	0.535 (9)	0.521 (9)	0.470 (7)	0.782 (6)	0.492 (10)	0.519 (10)	0.299 (9)
P10	0.555 (8)	0.542 (8)	0.483 (6)	0.781 (7)	0.533 (8)	0.548 (7)	0.372 (8)
P11	0.611 (6)	0.599 (6)	0.418 (10)	0.816 (5)	0.550 (7)	0.560 (6)	0.756 (2)
P12	0.634 (4)	0.622 (4)	0.505 (5)	0.831 (2)	0.623 (4)	0.614 (4)	0.634 (5)
P13	0.662 (3)	0.660 (3)	0.666 (2)	0.692 (9)	0.663 (3)	0.664 (2)	0.611 (6)
P14	0.670 (2)	0.661 (2)	0.549 (3)	0.821 (4)	0.680 (2)	0.678 (1)	0.736 (4)
P15	0.623 (5)	0.611 (5)	0.440 (9)	0.824 (3)	0.570 (6)	0.595 (5)	0.752 (3)

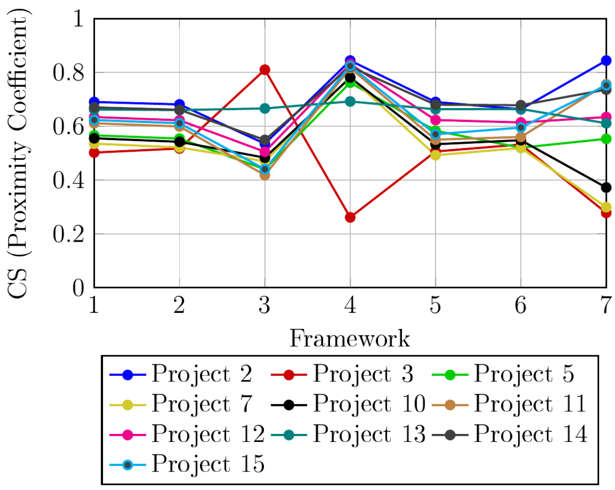

Fig. 4. Optional Project ranking of different frameworks

Fig. 4 illustrates the changes in proximity coefficients of the projects based on the different Frameworks. The best-ranked project is Project 2. Project 2 is the best alternative for the frameworks CRITIC method, equal weights, risk and priority and sustainability. P14 is the best alternative for the strategy framework. The worst-ranked alternative is Project 3, which is the least favourable for the frameworks CRITIC method, equal weights, Risk and sustainability but the best alternative for the framework economic. Project 11 is the least favourable for the framework economic, and Project 7 least favourable for the frameworks priority and strategy. The results indicate that, in this specific case, Framework 2 is redundant, as its weightings are similar to those of Framework 1. However, we would like to emphasize that Framework 2 (equal weights) may still be valuable for other case studies. Nevertheless, it will not be further considered in the sensitivity analysis conducted in this work.

In summary, it can be observed that the ranking of projects varies depending on the weighting of the evaluation criteria. A particularly striking example is Project P3. While it appears in the lower ranks in most evaluation frameworks, it takes the top position within the economic framework. This illustrates how crucial the weighting of criteria are, and that they should be aligned with the company's specific requirements.

From the variation of the weights, it can be observed that the rankings change. The Spearman rank correlation coefficient can help to highlight the difference in ranks when the weights vary. Under the condition that there are no two projects with the same rank, equation 33 can be used to calculate the rank correlation between two different rank mappings (Li et al., 2022).

$$\boldsymbol{\rho = 1 - \frac{6\sum_{i=1}^{z} d_i^2}{z(z^2-1)}} \tag{33}$$

The values d_i $(i = 1,2,\dots,z)$ represent the differences $d_i = R(x_i) - R(y_i)$ between the ranks of x_i and y_i. A value of 1 indicates a perfect positive correlation between the rank orders, while a value of -1 indicates a perfect negative correlation.

Table 9
Spearman Rank Correlation on different Frameworks

Framework	**FW 1**	**FW 3**	**FW 4**	**FW 5**	**FW 6**	**FW 7**
FW 1	1	0.188	0.636	0.952	0.903	0.794
FW 3	0.188	1	-0.285	0.297	0.406	-0.309
FW 4	0.636	-0.285	1	0.491	0.442	0.770
FW 5	0.952	0.297	0.491	1	0.842	0.673
FW 6	0.903	0.406	0.442	0.842	1	0.636
FW 7	0.794	-0.309	0.770	0.673	0.636	1

Table 9 presents the various Spearman rank correlations for the different rank Frameworks. For example, Framework 1 and Framework 5 exhibit a very strong positive correlation with a ρ-value of 0.952. However, the results reveal that the ranking orders of the frameworks differ in all cases. Therefore, it would be advisable to conduct a further analysis.

The agreement between Framework 1 and the remaining Frameworks can be determined by measuring the degree of variance of the MCDM technique using an error metric. Consequently, the Mean Absolute Percentage Error (MAPE) is used to assess the agreement of the cases. MAPE is calculated using Eq. (34).

$$\boldsymbol{MAPE = \frac{1}{n}\sum_{l=1}^{n}\left|\frac{A_l - O_l}{A_l}\right|} \tag{34}$$

A_l is the current value, taken as the basis for the changes (Framework 1) and O_l is the value predicted by the variation of the weights. Lewis (1982) defined that an error less than 10% leads to high agreement, an error between 10% and 20% to good agreement, an error between 20% and 50% to moderate agreement, and an error greater than 50% to weak and inaccurate results. According to this definition, a lower error percentage indicates better agreement for the cases. The MAPE results between Framework 1 and the other Frameworks 3 to 7 are illustrated in Fig. 5.

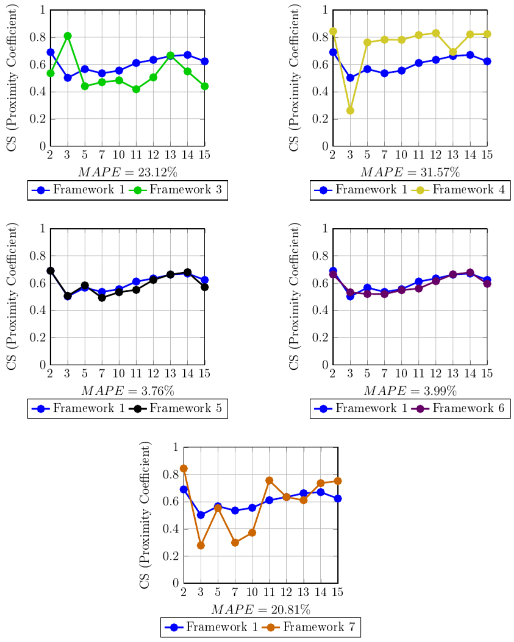

Fig. 5. MAPE between Framework 1 and other Frameworks of optional Projects (rounded to two decimal places)

In the comparisons between Framework 1 (CRITIC) and Framework 5 (Priority), the values of $MAPE = 3.76\%$ show a high agreement according to the definition (Lewis, 1982). The Strategy Framework (Framework 6), with a $MAPE$ of 3.99%, also demonstrates high agreement. In contrast to these Frameworks, the Frameworks Sustainability (Framework 7) with $MAPE = 20.81\%$, Economic (Framework 3) with $MAPE = 23.12\%$ and Risk (Framework 4) with $MAPE = 31.57\%$ shows a moderate agreement.

The error analysis with MAPE provides a meaningful assessment of the sensitivity of the criteria (Dhara et al., 2022). A high error measure indicates a high sensitivity of the criterion. The most sensitive criterions is, therefore, the Risk criterion. The least sensitivity is shown by the Priority criterion.

A sensitivity analysis for the mandatory projects was conducted and is presented in Appendix A. The results show that the risk criterion also has the highest sensitivity in the mandatory projects. In contrast to the optional projects, the strategy criterion has the lowest sensitivity in the mandatory projects.

6. Example of a project portfolio selection

Table 10 presents the evaluation values CS_j for projects P1-P15. Each project requires resources with various skills for execution. In this example, resources with skills S1-S3 are needed to carry out a project. At least one resource with each required skill is necessary for project implementation. For instance, to execute Project P1, 2.2 packages of resources with skill S1 and 1.4 packages of resources with skill S2 are required. For the sake of simplicity, the fixed package size for all resource skills is $srp_b = 50$ mandays. The company has 14 packages for skill S1, 13 packages for skill S2, and 9 packages for skill S3. This results in $TS_1 = 14 * 50 = 700$ mandays of resources available for skill S1, $TS_2 = 13 * 50 = 650$ mandays for skill S2, and $TS_3 = 9 * 50 = 450$ mandays for skill S3.

Table 10
Example of evaluated Projects

Project	Characteristic	CS	NPV	Sustainability	nrp_1	nrp_2	nrp_3
P1	man	0.507	16300	13000	2.2	1.4	0
P2	opt	0.690	6000	-4500	1.1	1.6	2.2
P3	opt	0.502	25000	19000	2.1	0.8	0.2
P4	man	0.284	-14000	10000	1.6	2.6	1.3
P5	opt	0.566	2500	6000	1.2	0.1	0
P6	man	0.458	-5000	10000	2.5	1.4	0.1
P7	opt	0.535	4000	15000	0	1.6	1.4
P8	man	0.604	12000	15000	0.8	1.5	0.8
P9	man	0.582	-2000	-2000	2.8	0.7	2.8
P10	opt	0.555	4500	12000	0.4	1.8	0.4
P11	opt	0.611	1000	-1000	1	0.6	0
P12	opt	0.634	5000	4000	2	1	0.6
P13	opt	0.662	12000	5000	0.6	0.4	1.6
P14	opt	0.670	6800	1000	1.2	1.4	0.8

P15	opt	0.623	2000	-500	0.2	1	1

For the sake of simplicity, the emission package size is $sep = 1000$, and the total CO2 emission limit is $SLMT = 70 * 1000 = 70{,}000$. The value of the target function of the optimal project portfolio is

$$\boldsymbol{z = 5.555} \tag{35}$$

In total, 10 projects were selected for the optimal project portfolio: P1, P4, P6, P8, P9, P10, P11, P13, P14, and P15.

6.1 Sensitivity analysis for the project portfolio selection

Sensitivity analysis plays a crucial role in integer programming approaches for project portfolio selection. Even small changes in the parameters can impact the results and lead to a different selection of projects. It is important that the decision-makers agree with the outcomes of the existing project portfolio so that it meets their requirements (Tavana et al., 2015)

For the sake of simplicity and clarity, the sensitivity analysis is experimentally performed on a representative example. The parameter values of the available resources TS_b and the upper limit of CO2 emissions $SLMT$ are gradually modified to examine the points at which changes in the portfolio occur. The values will be adjusted both upward and downward. For the sake of simplicity, only one parameter is varied at a time while all others are kept constant, and the corresponding simulations are conducted on this basis. Once a resource has been fully analyzed, the next one proceeds and adjusts its parameters accordingly.

Table 11 shows the changes in the objective function values when the number of available resources is modified. The projects selected in the different scenarios are listed in this table. The given NPV values show the cumulative NPV of the selected projects. It can be observed that an increase in the objective function values does not necessarily lead to a higher total NPV.

Table 11
Sensitivity Analysis on the Company's Available Resources

Case	nrp_1	nrp_2	nrp_3	nep	Selected Projects	Objective Value	NPV
1	14	13	9	70	P1, P4, P6, P8, P9, P10, P11, P13, P14, P15	5.555	33,600
2	13	13	9	70	P1, P4, P6, P8, P9, P11, P13, P14, P15	5.000	29,100
3	15	13	9	70	P1, P4, P5, P6, P8, P9, P10, P11, P13, P14, P15	6.122	36,100
4	14	12	9	70	P1, P4, P5, P6, P8, P9, P10, P11, P13, P15	5.451	29,300
5	14	14	9	70	P1, P2, P4, P6, P8, P9, P10, P11, P14, P15	5.584	27,600
6	14	13	8	70	P1, P4, P5, P6, P8, P9, P10, P11, P14, P15	5.460	24,100
7	14	13	10	70	P1, P2, P4, P5, P6, P8, P9, P11, P13, P15	5.586	30,800
8	14	13	9	62	P1, P2, P4, P5, P6, P8, P9, P10, P11, P15	5.480	23,300

Case 1 represents the baseline scenario. In Case 2, the number of resource packages for Skill 1 is reduced by one, and in Case 3, it is increased by one. It can be observed that both the objective function value and the project portfolio change accordingly. In Case 2, Project 10 is no longer included in the portfolio, and the objective function value decreases to $z = 5.000$. Starting from the baseline: if, as in Case 3, the number of resource packages for Skill 1 is increased by one, Project P5 is added to the portfolio, and the objective function value increases to $z = 6.122$.

If the number of resource packages for Skill 2 is decreased by one compared to the baseline, the objective function value drops to $z = 5.451$. In this case, the number of projects in the portfolio remains the same, but Project P14 is replaced by Project P5. A similar effect is observed when the number of resource packages for Skill 2 is increased by one: Project P13 is replaced by Project P2, and the objective function value is $z = 5.584$.

In Case 6, starting from the baseline scenario, the resource package for Skill 3 is reduced by one, resulting in a decrease of the objective function value to $z = 5.460$. In this case, Project P5 is selected instead of Project P13. However, if the resource package is increased by one, the objective function value rises to $z = 5.584$. In this case, Projects P2 and P5 are selected instead of Projects P10 and P14.

When comparing Cases 5 and 7, the objective function values are quite similar. However, the key difference lies in the selected projects: while Case 5 includes projects P10 and P14, Case 7 selects projects P5 and P13 instead. This example highlights an important insight — variations in resource parameters can lead to different project portfolios being chosen, even when the resulting objective values remain similar. In such situations, decision-makers must carefully assess which portfolio better meets the company's overall requirements.

Should a tie occur between two candidate portfolios, the decision makers may rely on supplementary criteria to reach a final decision.

In contrast to the other resource packages, Sustainability shows no changes when the number of resource packages is increased or decreased by one package compared to the baseline. A change only occurs when the number drops to 62. In this case, the objective function value is $z = 5.480$, and Projects P2 and P5 are selected instead of Projects P13 and P14. No change in the objective function value is observed when the number of sustainability resource packages is increased. Fig. 6 illustrates the change in the objective function value as the number of sustainability packages is reduced from 70 to 50. The figure shows that a further reduction of the limit increasingly restricts the company's options in project selection. The red dot marks the starting point where the change is made.

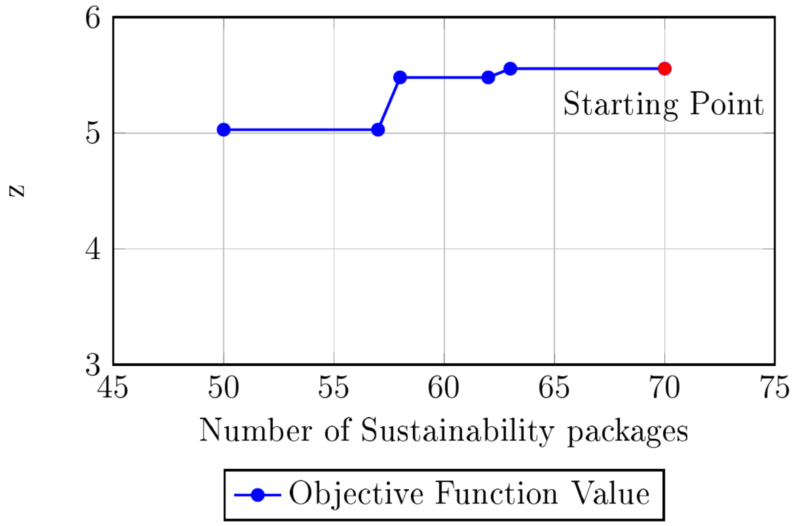

Fig. 6. Changes in Objective Function Values Due to Reduction of Sustainability package number

Fig. 7 shows how the objective function changes when each of the resource parameters is varied individually. The adjustments are made in both increasing and decreasing directions. In the top graph, the number of resource packages with skill 1 is modified. It is clearly visible that the objective function increases as the number of packages rises. Conversely, a reduction in the number of packages leads to a decrease in the objective value. A similar trend can be observed for the resource packages with skill 2 and skill 3.

If the company had the opportunity to purchase an additional resource package with either skill 1, skill 2, or skill 3, it should opt for the package with skill 1. This choice results in the highest value of the objective function.

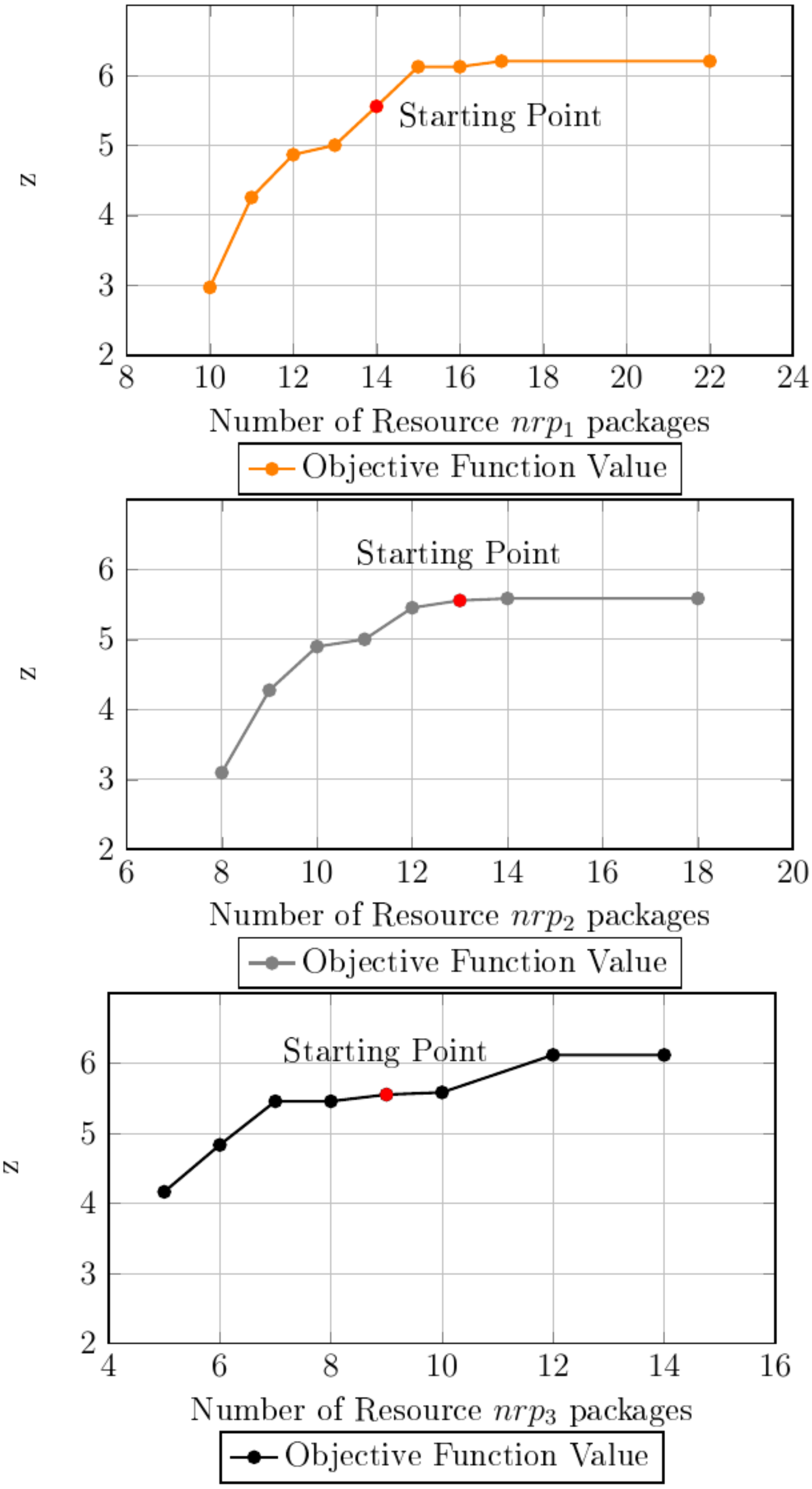

Fig. 7. Changes in Objective Function Values Due to the Change in Remaining Resources package numbers of nrp_1, nrp_2 and nrp_3

7. Conclusion and future work

The increase in volume of potential projects, driven by various factors such as digitalization, is prompting companies to seek a robust evaluation and evaluation process. This research presents an adaptive, scalable, and easily calibratable TOPSIS-MTPMMCBC model for multi-criteria decision-making, which evaluates and ranks projects based on a set of criteria: economic, risk, priority, strategy, and sustainability.

The proposed model can be expanded with additional or alternative business criteria, such as industry-specific criteria. Furthermore, criteria can be divided into sub-criteria or KPIs. For example, the sustainability criterion can include sub criteria such as environmental and social. These sub-criteria can include further KPIs.

In this model, projects are categorized based on their characteristics into three types: mandatory projects that generate positive NPV, mandatory projects that generate negative NPV, and optional projects. An initial solution for a sample set of projects was conducted. The proposed model particularly demonstrated that projects with mixed values like negative and positive NPV, meaning those that either incur costs or financial return for the company, can be included in the evaluation process. This is a highly important aspect, because companies not only have to make financial returns, but also invest in projects that only generate costs, for example to comply with government regulations. Projects can generate either positive or negative emissions in relation to sustainability.

The sensitivity analyses conducted in this study were based on experimental examples and addressed both the sensitivity of the proposed criteria and the selection of project portfolios. This methodological simplification serves to enhance comprehensibility. The criteria weights were objectively calculated using the CRITIC method, and the results of the evaluation process were compared with the evaluation results in which the criteria weights were varied. While the priority criterion showed the least sensitivity, the risk criterions exhibited the highest sensitivity among the criteria. This interpretation applies to the given example.

With regard to the project portfolio, the parameters related to company resources were varied. It was shown that changes in these parameters can lead to different project selections. The resulting solutions must always meet the specific requirements of the company. In future research, sensitivity analyses should be examined more thoroughly and assessed in terms of their general validity.

One of the assumptions for the initial solution was that the criterias are independent of each other. However, in the real world, the criteria may not be independent. This can be explained by simple causal relationships. Projects that are highly focused on sustainability can, for example, lead to the generation of grants or tax incentives. Consequently, this would be reflected in the NPV and eventually affect the risk metric. These interdependencies should be analyzed and interpreted more explicitly in further research work.

In the literature, several TOPSIS models are concerned with project evaluation and ranking. From the literature review presented in this work, it can be seen that a large portion of the cited studies combine TOPSIS with Fuzzy Logic. Our initial goal was to develop a functional and robust model. A further step could be the integration of Fuzzy Logic into the model we propose. The fundamental idea is to transform the given values into fuzzy sets. Experts can provide their evaluations using linguistic terms such as "high," "medium," or "low," which are then converted into fuzzy numbers.

In a further research, the proposed model is to be applied to the project sequenceing for optimization purposes. The TOPSIS-MTPMMCBC model will play a crucial role in assessing the projects, and the resulting evaluations will be utilized to determine the sequence in which the projects should be executed. By integrating the model into the project sequencing process, a usable model of the decision making process and sequencing should be presented on a plausible basis for project management.

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Appendix A.

Appendix A.1 Sensitivity analysis of Mandatory Projects

Table A.1 presents the proximity coefficients $CS_{j,c}$ of mandatory projects and the rankings for all Framework. The values are rounded to three decimal places.

Table A.1
Proximity Coefficients Values and rankings of mandatory projects on different Frameworks

Project	FW 1 CRITIC	FW 2 Equal W.	FW 3 Economic	FW 4 Risk	FW 5 Priority	FW 6 Strategy	FW 7 Sustainability
P1	0.507 (3)	0.519 (3)	0.731 (1)	0.315 (5)	0.527 (3)	0.501 (3)	0.342 (4)
P4	0.284 (5)	0.273 (5)	0.096 (5)	0.418 (4)	0.353 (5)	0.317 (5)	0.353 (3)
P6	0.458 (4)	0.441 (4)	0.266 (4)	0.716 (3)	0.466 (4)	0.432 (4)	0.400 (2)
P8	0.604 (1)	0.596 (1)	0.656 (2)	0.78591 (2)	0.611 (1)	0.602 (1)	0.323 (5)
P9	0.582 (2)	0.569 (2)	0.352 (3)	0.78598 (1)	0.592 (2)	0.587 (2)	0.761 (1)

Fig. A.1 illustrates the changes in proximity coefficients of the mandatory projects based on the different Frameworks. The best-ranked project is Project 8. Project 8 is the best alternative for the frameworks CRITIC method, equal weights, priority and strategy. Project 1 is the best alternative for the framework economic. The best alternative for the framework risk and sustainability is project 9. The worst-ranked alternative is Project 4, which is the least favourable for the frameworks CRITIC method, equal weights, economic, priority and strategy. Project 1 is the least favourable for the framework risk and Project 8 the least favourable for the framework sustainability.

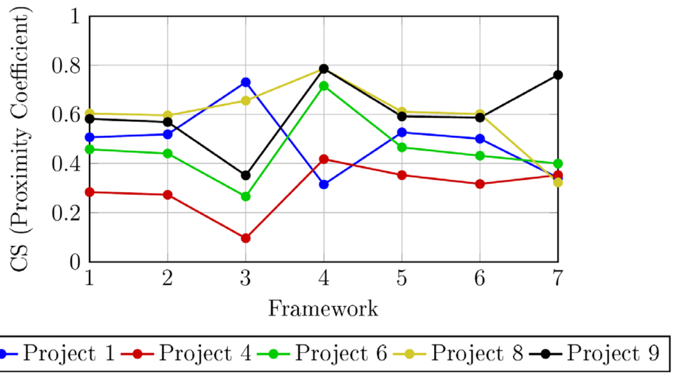

Fig. A.1. Mandatory Project ranking of different frameworks

In the comparisons between Framework 1 (CRITIC) and Framework 6 (Strategy), the values of $MAPE = 3.90\%$ show a high agreement according to the definition. The Priority Framework (Framework 5), with a MAPE of 6.55%, also demonstrates high agreement. In contrast to these Frameworks, the Frameworks Sustainability (Framework 7) with $MAPE = 29.31\%$, Economic (Framework 3) with $MAPE = 40.15\%$ and Risk (Framework 4) with $MAPE = 41.31\%$ shows a moderate agreement.

A high error measure indicates a high sensitivity of the criterion. The most sensitive criterions is, therefore, the Risk criterion. The least sensitivity is shown by the Strategy criterion. The $MAPE$ results between Framework 1 and the other Frameworks 3 to 7 are illustrated in Fig. A.2.

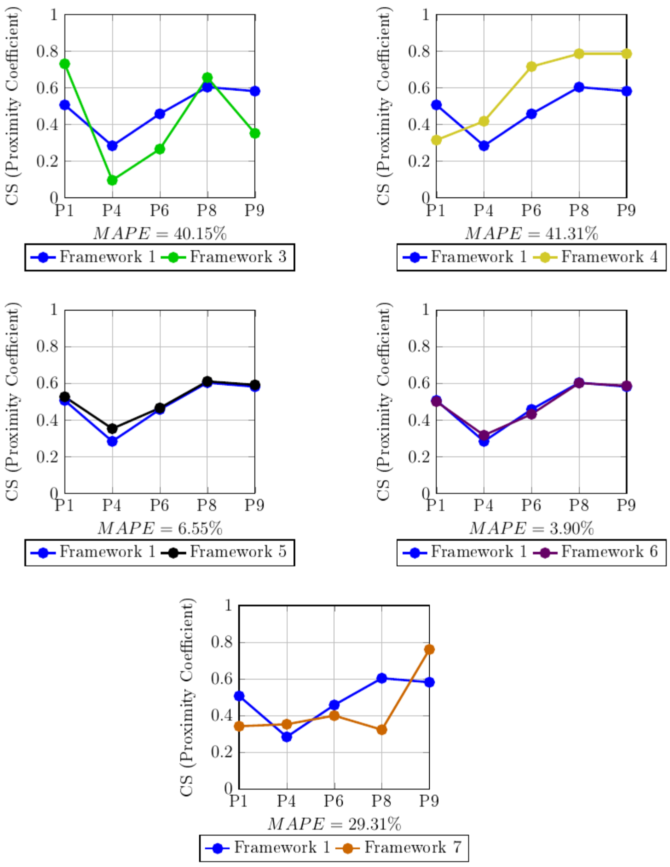

Fig. A.2. MAPE between Framework 1 and other Frameworks of mandatory Projects (rounded to two decimal places)