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ORIGINAL PAPER

Modelling decision knowledge for the evaluation of water management investment projects

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Abstract

Water resources are facing increased stress owing to population growth and environmental pollution. Water utility companies are concerned about this, and they are increasingly utilizing decision support systems to achieve higher transparency in utility investment project selection and to improve the economic management of water supply systems and resource exploitation. However, utility investment project decisions involve a diverse set of quantitative and qualitative criteria. This makes the selection of an appropriate decision method difficult. We have developed a novel hybrid multi-criteria decision method that integrates quantitative and qualitative criteria value domains in the same decision-making model and applied it to a real-world case involving a large multi-utility operator. The method is based on the decision expert and multi-attribute utility theory methods, which were modified to facilitate conversion between criteria domains. Our innovative approach allows for the use of the expressive power and comprehensibility of the qualitative method while maintaining the precision of the quantitative method, enabling decision makers to differentiate more easily between worthwhile and less feasible utility investment projects in the field of safe drinking water supply. The proposed method is applicable to a wide range of decision problems involving a diverse set of decision criteria.

Keywords Multi-criteria decision method · Modelling decision knowledge · Quantitative and qualitative knowledge modelling · Investment project ranking · Effective water utility management

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1 Introduction

The efficient planning of drinking water infrastructure in the form of distribution networks and treatment plants depends on future water demand and socio-economic considerations (Vörösmarty et al. 2000; Hoque 2014). Unexpected increase in water demand can cause severe shortages in the provision of services, restricting public access to drinking water and sanitary services. In addition, it can cause considerable decline in water resources (Vörösmarty et al. 2000; Basupi and Kapelan 2013; Hoque 2014). Therefore, it is important to be aware of current problems and anticipate the challenges of future generations. These challenges can be adequately overcome through efficient planning in all phases of a utility investment project, such as the new construction, restoration, and replacement of water supply systems, and the management of water distribution networks (Zayed and Mohamed 2013).

In this paper, we present the development of a novel multi-criteria decision method (MCDM) and its validation with a decision model created for an utility investment project selection in a 70-year-old multi-utility service company (subsequently referred to as "operator"). This company operates numerous utility investment projects (subsequently referred to as "projects") in the field of water distribution management for various water supply companies (subsequently referred to as "customers"). It is one of the largest companies in South Eastern Europe, with over 5000 employees.

The decision problem faced by the operator involves the ranking of proposed projects in the field of water supply management. The projects are acquired through tenders, which are a part of the drinking water supply investment programs of customers, i.e., water utility companies. Each project concerns a single customer and their water supply system. Within a project, the operator implements a water distribution network control and monitoring system that allows for the supervision of distribution paths and water consumption, both of which play a significant role in water loss identification (Basupi and Kapelan 2013; Zayed and Mohamed 2013). Projects are undertaken as collaboration between the operator and a customer and typically last for several years. Therefore, project ranking influences the operator's long-term work resource planning, e.g., the work plans of project implementation teams.

Proposed projects are evaluated and selected by the sales department of the operator. The decision makers' goal is to find suitable customers with whom they will engage on a long-term basis in projects aimed at optimizing water supply systems. Until now, the decision process was carried out ad hoc during the meetings of departmental managers without systematic methodological support. Decisions were based on non-systematised knowledge and were difficult to justify. To improve the decision process, the operator has requested our assistance in providing systematic decision support for project evaluation. Our aim is to support the process with an easy to understand decision model that would increase the transparency of the process, improve the quality and consistency of decisions, and make their justification easier.

However, investment project decisions involve a diverse set of quantitative and qualitative criteria. Some criteria may have poorly defined or uncertain values, making the selection of an appropriate decision method difficult. For this purpose, we have developed a novel hybrid MCDM (HMCDM), which is based on the multi-attribute utility theory (MAUT) and decision expert (DEX) methods (Fishburn 1967; Fishburn and Keeney 1974; Kolios et al. 2016). The method supports two types of utility functions, i.e., weighted sum for quantitative criteria and *if–then* rules for qualitative criteria, and implements a novel algorithmic criteria type conversion function to support both types of criteria. The main aspect of the novel HMCDM is the possibility of non-destructively converting a quantitative criterion into a qualitative criterion, maintaining both the original quantitative criterion with (more precise) values and the additional qualitative criterion. This enables us to simultaneously conduct the quantitative and qualitative evaluation of a criterion and considerably improve model transparency, flexibility, and accuracy.

We have applied the novel HMCDM in developing a decision model consisting of quantitative and qualitative criteria for project evaluation using the input from the operator's team of experts. The model enables decision makers to overcome certain disadvantages of using an exclusively qualitative or quantitative methods. In this manner, we retain the original accurate values of criteria throughout the model and determine small differences among decision variants in the final evaluation.

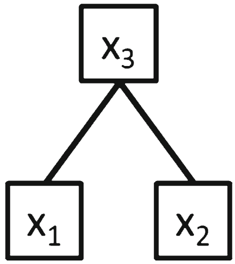
The rest of this paper is organised as follows: First, the methodological foundations of the novel HMCDM are described. Second, the novel HMCDM is presented, with emphasis on the method for the combination of qualitative and quantitative criteria. The subsequent section presents the model developed for a real-life decision problem, which we used to validate the method, followed by the model evaluation results of four real-life projects. Then, a discussion of evaluation results as seen by the operator's expert team is presented, followed by the summary of the work's contributions to science and applied knowledge. Finally, the conclusions of the study are presented.

We have validated the novel HMCDM in the field of water supply management. However, it can also be applied to decision problems in other fields where a transparent combination of qualitative and quantitative criteria would be beneficial.

2 Method

The novel HMCDM follows the general principles of the MCDM, i.e., within a finite set of decision variants, every variant is evaluated using a model consisting of a finite set of criteria (attributes) $X = \{x_1, x_2, \ldots, x_n\}$, where n denotes the number of criteria in a set. The structure of an MCDM model is represented by an inverted tree (criteria tree), where the lowest criteria are referred to as elementary or basic criteria. These criteria represent the basic measurable characteristics of decision variants. Higher-level criteria are composed of two or more lower-level criteria, and thus, they are referred to as aggregated criteria. In the evaluation of a decision variant, the values of criteria are measured (elementary criteria) and calculated (aggregated criteria) in a bottom-up manner using an aggregated utility function until the topmost aggregated criterion is calculated. The value of this criterion represents the general score of the decision variant, and it is used to compare the variant with other variants (Fan et al. 2014; Hoque 2014; Olsson 2015; Bohanec et al. 2017). For the purpose of illustration, Fig. 1 shows the hierarchical structure of three criteria, where x_1 and x_2 represent basic criteria and x_3 represents an aggregate criterion.

Fig. 1 Simple criteria tree



Each criterion x_i has its intrinsic domain $D_{(x_i)}$. The domain for quantitative criteria can be defined as $D_{(x_i)} = \left\{x_i : x_i, x_i^{least}, x_i^{most} \in \mathbb{R},\ x_i^{least} \le x_i \le x_i^{most}\right\}$, where x_i^{least} and x_i^{most} denote the least and most desirable values in domain $D_{(x_i)}$, respectively. The domain for qualitative criteria can be defined as $D_{(x_i)} = \left\{d_{x_{i1}}, d_{x_{i2}}, \ldots, d_{x_{im}}\right\}$, where m denotes the number of possible values in domain $D_{(x_i)}$. In the novel method, the domains of all criteria are ordered from the least desired value $d_{x_{i1}}$ to the most desired value $d_{x_{im}}$. If criterion x_i is aggregated, its value is calculated from its subordinate criteria in set $Z \subseteq X$ using aggregated utility function f or $x_i = f(Z)$ (Fan et al. 2014; Hoque 2014; Olsson 2015; Bohanec et al. 2017).

In the novel HMCDM, we distinguish between the following types of values that can be assigned to a criterion depending on its type:

- x_i^{quant}: quantitative value
- x_i^{qual}: qualitative value (class assessment)

Therefore, the criteria values belong to:

$$X^{quant} = \left\{x_1^{quant}, x_2^{quant}, \ldots, x_n^{quant}\right\}$$

$$X^{qual} = \left\{x_1^{qual}, x_2^{qual}, \ldots, x_n^{qual}\right\}$$

We use the MAUT method to aggregate two or more quantitative criteria into a higher-level quantitative criterion (as presented in Sect. 2.2). We use the DEX method to aggregate qualitative criteria into a higher-level qualitative criterion (as presented in Sect. 2.3). Our method for the aggregation of quantitative and qualitative criteria is presented in Sect. 2.4.

2.1 Hybrid MCDM

The combination of quantitative and qualitative MCDMs has been the subject of theoretical treatises earlier, e.g., Yang (2001) and Mihelčić and Bohanec (2017). The DEX method has been used as a part of a hybrid MCDM named "Qualitative-quantitative method" (QQ) as early as Bohanec et al. (1992) which also appears in recent publications (Mileva Boshkoska et al. 2015). However, to the best of our knowledge, the proposed approach of combining the MAUT and DEX methods with transformation of criteria domains and subsequent quantitative and qualitative evaluations of the criteria tree has not been the subject of a previous research presented in a scientific paper.

Zavadskas et al. (2016) presented an overview of HMCDMs based on a sample of 2450 scientific publications the Web of Science Core Collection published from 1999 to 2015. The authors state that while several new approaches for HMCDMs have been developed and published in recent years, there is a lack of a critical review of these methods. The most frequently used MCDMs in reviewed research include the analytical network process (ANP), decision making trial and evaluation laboratory model (DEMATEL), technique for order preference by similarity to ideal solution (TOPSIS), analytic hierarchy process (AHP), and "Vlsekriterijska optimizacija i KOmpromisno Resenje" (VIKOR). An interesting observation is that water management ranks lowest in the overview of 32 research areas that utilise HMCDMs. The majority of research is in seven areas, i.e., computer science, engineering, operational research and management science, business economics, mathematics, energy fuels, and environmental sciences ecology.

According to Zavadskas et al. (2016), several shortcomings of singular MCDMs can be solved by combining two or more methods into a hybrid method and developing a set of recommendations for decision makers. Mardani et al. (2015) and Zavadskas et al. (2016) stated that for complex decision problems, the selection of an appropriate method involves compromises and trade-offs. No method can be considered as the "best" either for a general or for a particular problem. Furthermore, different MCDMs can yield different rankings of decision variants. Zavadskas et al. (2016) proposed the modelling of a problem using several methods and integrating results. However, the integration of results poses an additional decision problem. Furthermore, decision-making models should be as close as possible to real-life problems, which typically involve a degree of uncertainty that can be modelled by integrating fuzzy sets or probabilities in decision-making models.

Chaising and Temdee (2017) described an example of an HMCDM by integrating the Fuzzy AHP and TOPSIS methods for decision support in selection of raw material suppliers for a small and medium-sized enterprise (SME). The Fuzzy AHP method has been used to handle the ambiguity and uncertainty of criteria, and the TOPSIS is applied to rank supplier variants as the final result. In Shafique (2017), the research is focused on the development of hybrid MCDM model for green supplier selection. The proposed method is based on three approaches, Decision Making Trial and Evaluation Laboratory Model (DEMATEL), the Analytical Network Process (ANP), and TOPSIS. Lin et al. (2007) presented a decision problem of offshore location selection and proposed the use of the AHP method and preference ranking organization method for enrichment of evaluations (PROMETHEE) methods for offshore location selection decisions. The AHP method was used to analyse the structure of the location selection problem and determine the weights of criteria, and the PROMETHEE method was used for the final ranking along with various weights for sensitivity analysis.

In the following sections, we present the theoretical basis for the novel hybrid method and the application of the method to a real-world example.

2.2 Quantitative criteria

The MAUT method uses quantitative value domains. MAUT aims to calculate a unique number (value) that represents the overall strength of each alternative, considering all criteria. The basis of MAUT is the use of utility functions, whose purpose is to create a mathematical model to aid the decision process (Fishburn and Keeney 1974; Keeney 1977; Dyer 2005).

In MAUT, a multi-attribute utility function describes the preferences of a decision maker. The function depends on the axioms of preferential, utility, and additive independence for normative decision making (Fishburn and Keeney 1974; Keeney 1977; Dyer 2005).

The utility theory is used in decision analysis to transform the raw performance values of alternatives against diverse criteria to a common dimensionless scale. The MAUT method includes different aggregation models, but the most used model is the additive aggregation model. Additive aggregation, i.e., weighed sum, is based on the mathematical concept of weighted means. It can be formulised as a utility function, as shown in Eq. (1) (Fishburn and Keeney 1974; Keeney 1977; Dyer 2005).

$$x_i^{quant} = \sum_{j=1}^{n} w_j x_j^{quant} \tag{1}$$

where x_i^{quant} has n (two or more) subordinate criteria and w_j represents the weight of criterion x_j^{quant}.

The multi-attribute utility function is a linear combination of the utility functions of criteria, which may be linear or nonlinear (e.g., logarithmic and piecewise) (Fishburn and Keeney 1974; Keeney 1977; Dyer 2005).

2.3 Qualitative criteria

Our method uses DEX as the basis for the treatment of qualitative criteria. DEX is a qualitative hierarchical MCDM; it was first proposed by Bohanec and Rajkovič (1990). DEX differs from other multi-attribute decision support systems in that it uses qualitative (symbolic) attributes (with values such as "low", "medium", "high", "unacceptable", "acceptable", and "excellent") instead of quantitative attributes. Scales are typically small, and they contain 2–5 values that discriminate between the different important different characteristics of relevant decision variants. DEX employs the fuzzy or probabilistic distributions of values to evaluate incompletely or inaccurately defined variants. DEX primarily uses the method known as "selective explanation" to explain variant evaluation (Bohanec et al. 2013, 2017).

DEX is a rule-based method. Therefore, a utility function in DEX is defined by simple *if–then* decision rules in the form of decision tables rather than numerically by, for instance, weighted sum. Each rule defines the function for a specific set of values for each of its subordinated criteria (Bohanec et al. 2013, 2017).

For the case shown in Fig. 1, a simple rule may be represented as

$$If x_1^{qual} = d_{x_{1p}^{qual}} \quad and \; x_2^{qual} = d_{x_{2q}^{qual}} \quad then \; x_3^{qual} = d_{x_{3r}^{qual}}$$

where $d_{x_{1p}^{qual}}$ represents a value in domain $D_{(x_1^{qual})}$, which is specific for criterion x_1^{qual}, $d_{x_{2q}^{qual}}$ represents a value in domain $D_{(x_2^{qual})}$, which is specific for criterion x_2^{qual}, and $d_{x_{3r}^{qual}}$ represents a value in domain $D_{(x_3^{qual})}$, which is specific for criterion x_3^{qual}.

A qualitative utility function is defined when rules are set for all combinations of all possible values of its subordinated criteria. We can assess the weights of subordinated criteria based on the set of *if–then* rules using regression and the linear least squares method (Bretscher 1995; Bohanec et al. 2000; Bohanec 2015).

The weight of a single criterion is estimated by calculating the slope of the line that corresponds to the influence of subordinated criterion x_{sub}^{qual} on aggregate criterion x_{agg}^{qual} using the linear least squares method. This method requires the calculation of $v\left(x_i^{qual}\right)$ for every subordinate criterion x_{sub}^{qual} and the aggregate criterion x_{agg}^{qual}. The function v assigns value 0 to the least desired value of x_i^{qual} and value 1 to the most desired value of x_i^{qual}. The interval [0, 1] is then divided into equal subintervals depending on the number of values in the qualitative domain $D_{(x_i^{qual})}$. For example, individual qualitative values from $D_{(x_i^{qual})}$ that contains 3 possible values, e.g., $\{a, b, c\}$, are assigned quantitative values $v\left(x_i^{qual}\right) \in \{0, 0.5, 1\}$. Another requisite for weight assessment is for the domain $D_{(x_i^{qual})}$ to contain ordered values, starting with least desired value and ending with most desired value. The values $v\left(x_i^{qual}\right)$ are then to be used in Eq. (2):

$$slope\left(x_{sub}^{qual}\right) = \frac{\sum\left(v\left(x_{sub}^{qual}\right) - \bar{v}\left(x_{sub}^{qual}\right)\right) \times \left(v\left(x_{agg}^{qual}\right) - \bar{v}\left(x_{agg}^{qual}\right)\right)}{\sum\left(v\left(x_{sub}^{qual}\right) - \bar{v}\left(x_{sub}^{qual}\right)\right)^2} \tag{2}$$

where $\bar{v}$ denotes the mean value of all values of v; the sum runs through simple *if–then* rules.

The weight of criterion x_i, $w(x_i)$, is calculated using the ratio of the slopes of all subordinated criteria of an aggregate criterion Eq. (3):

$$w(x_i) = \frac{slope(x_i)}{\sum_{j=1}^{n} slope(x_j)} \tag{3}$$

where n denotes the number of subordinate criteria.

2.4 Combining quantitative and qualitative criteria

In this section we present the methodology that allows us to calculate both qualitative values and quantitative values for all qualitative criteria. Let us assume that we have a

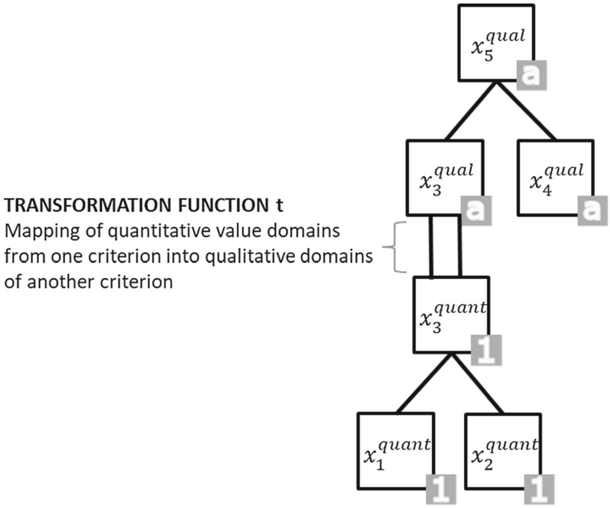


Fig. 2 Simple model with quantitative and qualitative criteria

hierarchical structure of six criteria, quantitative and qualitative, where x_1^{quant}, x_2^{quant}, and x_4^{qual} represent basic criteria and x_3^{quant}, x_3^{qual}, and x_5^{qual} represent aggregate criteria, as shown in Fig. 2. The criteria are presented as a tree structure with the following symbols: for quantitative criteria, for qualitative criteria.

2.4.1 Transformation of quantitative values into qualitative values

Quantitative criterion x_3^{quant} is transformed into qualitative criterion x_3^{qual} using transformation function t to allow its aggregation with the qualitative criterion x_4^{qual}. The transformation is indicated with a dual line connecting the x_3^{quant} and x_3^{qual}.

For each criterion x_i we define a value domain $D_{(x_i)}$. For quantitative criteria x_1^{quant},x_2^{quant}, and x_3^{quant} we define $D_{(x_i)} = \left\{x_i : x_i, x_i^{least}, x_i^{most} \in \mathbb{R},\ x_i^{least} \leq x_i \leq x_i^{most}\right\}$ with x_i^{least} and x_i^{most} being the least and most desired values for a criterion. For all qualitative criteria (x_3^{qual}, x_4^{qual}, x_5^{qual}), we define a qualitative domain with values ordered from the least desirable to the most desirable value. In our example, let us define the value domains for qualitative criteria as: $D_{\left(x_3^{qual}\right)} = \{a, b, c\}$, $D_{\left(x_4^{qual}\right)} = \{d, e, f\}$, and $D_{\left(x_5^{qual}\right)} = \{g, h, i\}$, and, to simplify the example, define that for each qualitative domain, its values can be translated into quantitative value ranges of equal width.

Using a weighted sum based on Eq. (1), we combine subordinate quantitative criteria x_1^{quant} and x_2^{quant} into aggregated criterion x_3^{quant}.

To allow transformation of x_3^{quant} to x_3^{qual}, we use a transformation surjective function t for the coexistence of both types of criteria in the same model. This function transforms the quantitative values of criterion x_i^{quant} into qualitative values of criterion x_i^{qual}.

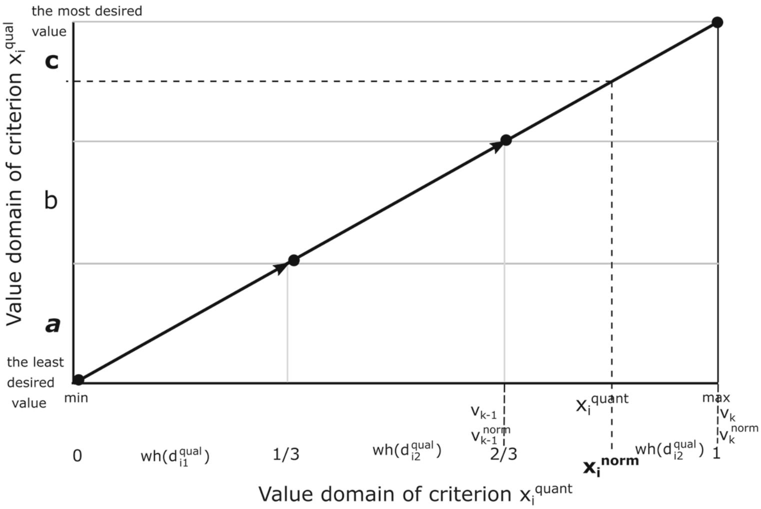


Fig. 3 Graphical presentation of a transformation function t that transforms quantitative values into qualitative values

$$x_i^{qual} = t\left(x_i^{quant}\right)$$

In function t, the value domain of criterion x_i^{quant} is split into k numeric intervals reflecting the qualitative values defined in the value domain of the target criterion x_i^{qual}. All values of x_i^{quant} within an interval $(v_{k-1}, v_k] = \left(v_{k-1} < x_i^{quant} \leq v_k\right)$ are mapped into a single qualitative value from the value domain $D_{(x_i^{qual})}$ of criterion x_i^{qual} as indicated in Fig. 3.

As a part of the transformation process, the quantitative value domains are normalised through a translation of $D_{(x_i)} = \{x_i : x_i, x_i^{least}, x_i^{most} \in \mathbb{R},\ x_i^{least} \leq x_i \leq x_i^{most}\}$ into $D_{(x_i)} = \{x_i : x_i \in \mathbb{R}, 0 \leq x_i \leq 1\}$. Here the natural scale of a quantitative criterion x_i^{quant} is normalised into the interval $\left[v_{k-1}^{norm}, v_k^{norm}\right] = [0, 1]$, with 0 and 1 as the least and most desirable values, respectively. Interval $\left(v_{k-1} < x_i^{quant} \leq v_k\right)$ is therefore transformed into interval $\left[v_{k-1}^{norm}, v_k^{norm}\right]$. We can refer to the normalised criterion as x_i^{norm}. Each qualitative value x_i^{qual} therefore corresponds to a range of quantitative values in the interval $(v_{k-1}, v_k]$. We define the width of this range, i.e., the width of qualitative value d_{xik}^{qual} as $wh\left(d_{xik}^{qual}\right) = v_k - v_{k-1}$, where $d_{xik}^{qual} \in D_{(x_i^{qual})}$.

A simple example of function t for transformation of x_i^{quant} to x_i^{qual}(e.g., from x_3^{quant} to x_3^{qual} as indicated by the double line in Fig. 2) is shown graphically in Fig. 3. In practice, a transformation function is defined by the decision makers, who define the quantitative and qualitative value domains of criteria and the translation from quantitative values (i.e., numeric intervals) into corresponding qualitative values. Values of x_i^{quant} can be defined by the decision makers either as exact values or estimates (numeric intervals). If we do not have an exact numerical value for x_i^{quant}, we can use interval assessment for x_i^{quant} by performing two calculations: one with the upper limit of the interval, and one with the lower limit of the interval.

Figure 3 shows that the value of x_i^{quant} is at the centre of the interval $(v_{k-1}, v_k]$, and therefore its value is mapped into qualitative value **c** using function t. In the process of converting x_i^{quant} to x_i^{qual}, we first need to normalise the value of x_i^{quant} to x_i^{norm} and thus obtain criterion value in the interval of [0, 1]. The formula Eq. (4) for normalization in our method can be expressed as

$$x_i^{norm} = \frac{x_i^{quant} - v_{k-1}}{v_k - v_{k-1}} \times wh\left(d_{x_{ik}}^{qual}\right) + \sum_{j<k} wh\left(d_{x_{ij}}^{qual}\right) \quad (4)$$

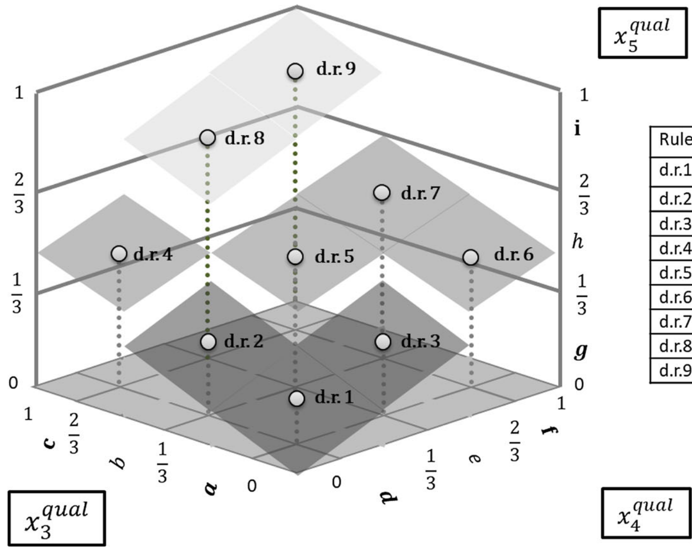
where the interval $(v_{k-1}, v_k]$ represents the range of quantitative values that are mapped into the same qualitative value $d_{x_{ik}}^{qual}$, $wh\left(d_{x_{ik}}^{qual}\right)$ describes the width of the qualitative value and k represents the qualitative value index.

In addition, decision makers define a set of *if–then* decision rules for criterion x_5^{qual} (Fig. 4). The rules are numbered from 1 to 9. In Fig. 3, the rules are marked with a dot and tag "d.r." (*if–then* decision rule). A decision rule can be defined with just two parameters (coordinates), i.e., the values of the subordinate criteria in an aggregation. Therefore, the value of aggregate criterion x_5^{qual} in Fig. 4 is completely determined by the values of x_3^{qual} and x_4^{qual}. Based on the defined set of *if–then* decision rules, we can calculate the qualitative value for criterion x_5^{qual} as well as the weights of subordinate criteria x_3^{qual} and x_4^{qual} using the method described in [Bohanec et al. 2000] and obtain the normalised values of the weights (sum of weights equals 1) as $w(x_3^{qual}) = 0.57$ and $w(x_4^{qual}) = 0.43$.

2.4.2 QUANQUAL algorithm: the qualitative–quantitative algorithm

Apart from converting the quantitative criteria into qualitative criteria in order to evaluate the criteria tree using qualitative decision rules, our methodology also allows the reverse: conversion of all qualitative criteria into quantitative criteria in order to perform quantitative evaluation of the criteria tree. In this procedure, we use the values of quantitative criteria as entered by the decision makers, and transform the values of qualitative criteria and their weights into equivalent ranges of quantitative values.

Using the QUANQUAL algorithm presented below, we are able to use the intrinsic values of quantitative criteria, thus maintaining accuracy. This way we are able to assign a quantitative value or value range to each aggregated qualitative criterion to more precisely define its value. The precision of assessment of the quantitative interval of an aggregated criterion depends on the precision of the values of subordinate criteria—using criteria with exact values as opposed to value ranges (estimates) results in a higher accuracy. The influence of a single criterion on the final result depends on the decision rules, the relative weight of the criterion, and the sensitivity of the



Rule	x_3^{qual}	x_4^{qual}	x_5^{qual}
d.r.1	*a*	*d*	*g*
d.r.2	*a*	e	*g*
d.r.3	*a*	f	h
d.r.4	b	*d*	*g*
d.r.5	b	e	h
d.r.6	b	f	h
d.r.7	c	*d*	h
d.r.8	c	e	i
d.r.9	c	f	i

Fig. 4 Graphical presentation of the utility function for criterion x_5

transformational function t. All these parameters are defined by the decision makers method.

An input for the QUANQUAL algorithm is the set of decision rules dr, which produce the final evaluation value qv of the evaluated variant (e.g., rules 8 and 9 in Fig. 4).

The algorithm calculates the quantitative interval $(v_{k-1}, v_k]$ which corresponds to the qualitative value $d_{x_{ij}}^{qual}$ (see Fig. 3) for each criterion x_i^{qual} that appears in a decision rule. The quantitative interval is defined by its upper and lower bounds, which are calculated by dividing the normalised scale interval [0, 1] divided into equal subintervals depending on the number of qualitative values in the domain $D_{(x_i^{qual})}$. For example, qualitative values from $D_{(x_i^{qual})}$ that contains 3 possible values, e.g., $\{a, b, c\}$, are converted into intervals [0, 1/3), [1/3, 2/3), and [2/3, 1]. Then the decision rules are grouped according to their prescribed output value. Within each group, decision rules are evaluated by summing the results of multiplication of the bounds of intervals by the weight of the corresponding qualitative criterion. The results for lower bounds for all criteria in the decision rule are summed, and results for upper bounds for all criteria in the decision rule are summed. This is repeated for all decision rules in the aggregation with the same prescribed output. The lowest sum of lower bound results is then the low estimate for our output value, and the highest sum of the higher bound results is the high estimate for our output value. The low and high estimates are then normalised. If the aggregate criterion contains a subordinate quantitative criterion, we can use the quantitative criterion's x_i^{norm} value (see Fig. 3). For detailed operation, please refer to the QUANQUAL algorithm below.

The QUANQUAL algorithm is written in pseudocode.

```
algorithm QUANQUAL is

    input: set of decision rules dr,
           qualitative value qv
    output: interval assessment [r_min, r_max] for qualitative value qv
(Note that decision rule d is made of multiple subordinate criteria)

    for each rule in dr do
        if result(rule) is equal qv do
                let min(rule) be minimum value and max(rule) maximal value
of each rule
        min(rule) <- 0
        max(rule) <- 0
            for each criterion in rule do
                min(rule) <- min(rule) + getLowBound(criterion) *
getWeight(criterion)
                max(rule) <- max(rule) + getHighBound(criterion) *
getWeight(criterion)

    return normQual([min{min(rule)) | rule in dr}, max{max(rule) | rule in
dr}])
```

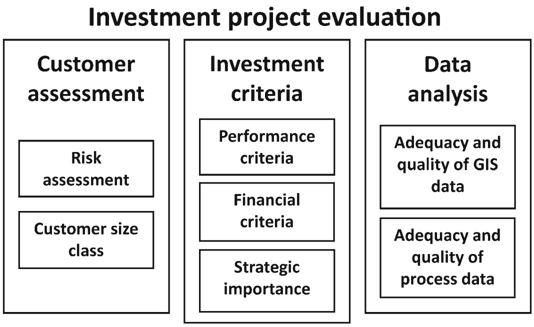
Function **getLowBound** returns the lower bound, while **getHighBound** returns the upper bound of a mapped qualitative value $wh\left(d_{x_{ij}}^{qual}\right)$, which is defined by the decision rule for the chosen criterion (see Fig. 4). If there is an accurate x_i^{norm} value for the specific criterion (Fig. 4), the function returns the exact value of x_i^{norm} instead of the lower and upper bounds. Function **getWeight** returns the weight of the criterion within interval [0, 1] (see Fig. 4). Function **normQual** defines the criterion's value within its assigned qualitative value in the interval [0, 1], where 0 and 1 denote the least and most desirable values in the qualitative domain.

3 Decision problem background

The purpose of the decision-making model described in this paper is to help the operator identify and rank investment projects that correspond to the operator's activities and have potential for reducing operating costs and water losses on a scale that would make the projects economically viable within the operator's business model. If several "excellent" (qualitative evaluation) projects are available, the company implements the projects in the order of quantitative ranking within the "excellent" class of projects, i.e., the best evaluated project is implemented first, followed by the second best, and so on, while resources are available.

Even though the operator's decision makers have several years of experience, they find the decision problem of selecting appropriate projects and focusing of the operator's resources to achieve the best results complex and difficult. As decisions have

Fig. 5 Overview of the top-level criteria in the proposed hierarchical multi-criteria decision-making model



to be made in an early stage of a sales process, it is characteristic that the decision makers in sales departments do not have sufficient or precise information. This makes the process even more difficult. Considerable resources are involved in preparing the offer for a tender and during project implementation, e.g., the number of employees and their pay grade. Therefore, the operator's decision makers are under pressure to carefully select projects.

Until now, decision processes were carried out ad hoc at the meetings of departmental managers without systematic methodological support. Decisions were based on non-systematised knowledge and were difficult to justify. Therefore, the operator has requested our assistance in providing systematic decision support for project evaluation.

In the problem identification phase, we held several meetings and workshops with the operator's experts to fully identify and analyse the decision problem. This resulted in careful selection of a set of criteria used in their decision making.

The criteria were divided into three main groups, i.e., customer assessment, investment criteria, and data analysis (Fig. 5).

Decision makers require the following information to evaluate projects: the size of a customer's organization, the number and availability of employees to work on a project, the qualifications of employees, the credit ratings of the organization, its ownership structure, and the assessment of business risk in long-term collaboration with the customer (Alegre et al. 2017). For the success of complex and demanding long-term projects with a typical lifetime of 7 to 15 years, it is important that the customer is able to assign competent employees to maintain investment. A considered customer organization must have long-term stability to follow the goals of the project for 7 to 15 years. Therefore, the operator also considers the ownership structure of the customer organization and performs business risk assessment when selecting projects.

Decision makers assess the suitability of an investment from the standpoint of profitability, the size of bank guarantees, funding sources, the final deadline for project implementation, contractual obligations, and the type of contract. In addition, they assess the strategic importance of a project from the viewpoint of the operator. They want to know if, by accepting the project, the operator will be developing a new service for a market. Based on this newly developed service, they can acquire new customers or enter new markets. A successful project presents a good reference point for the operator to explore new business opportunities in future.

Additionally, strategic importance can be viewed from the standpoint of external opportunities (i.e., a customer's standpoint), which is presented in our decision-making model as a criterion named "external". This criterion considers two aspects, namely, "spare capacity" and "user growth trend". While the first criterion ("spare capacity") is related to the potential of water loss reduction, the second criterion ("user growth trend") considers the possible growth in water consumption and is mostly linked to the operation and condition of a water supply system (Vörösmarty et al. 2000; Kayaga et al. 2007; Martins 2014).

In addition to the aforementioned information, projects must be evaluated based on their data pertaining to the water supply system. Precise operational and infrastructure data are important for the successful completion of a project. While the precise operational data of hydraulic states are collected using measurement equipment, the data on the water supply system infrastructure are obtained from the geographic information systems (GISs) established based on water utility. These data form the basis for a well-calibrated hydraulic model of the water supply system, which can then be applied for the hydraulic analyses of different investigative scenarios (De Feo and De Gisi 2014; Kozelj et al. 2014).

Sales engineers can assess data quality from publicly accessible databases, such as a consolidated cadastre of public infrastructure and the annual reports of water utility, which include information on the water balance of the water supply system (Alegre et al. 2017). They use dedicated tools to check data and estimate the quality of each group of data in terms of points. To achieve a data completeness of 100 points (100%), experts spend several months in the implementation phase to match data to the actual state of the water supply system. Higher points imply faster and more rigorous implementation of projects. Experience shows that quality data are crucial for the implementation of a project, which is why the criterion of data was assigned considerable importance, i.e., weight.

To construct the criteria hierarchy tree, we added 14 aggregated criteria to the list of 30 criteria that were finalised in a brainstorming session. The root of the tree represents the final evaluation. The 30 basic criteria (leaves of the tree) have no subordinate criteria and are used to evaluate projects. Thus, we assessed the aggregated criteria using utility functions. We combined semantically similar criteria into groups while building the criteria tree. We used numerous aggregated criteria based on experiences with the DEX method, ensuring that a specific aggregated criterion does not have more than three sub-criteria. This action is directly linked to the complexity of expressing and describing utility functions. A large number of sub-criteria under one aggregated criterion increase the complexity of defining a utility function, which becomes unclear and difficult to manage for decision makers (Bohanec et al. 2013; Bohanec 2015).

We assigned short, unique, and easy-to-understand names to all criteria. We added a brief description for each criterion to facilitate the operator's understanding.

The criteria tree is presented in Fig. 6. The figure provides criteria descriptions and original value domains. Quantitative criteria include the units of measurement in addition to their value domains. The value domains of qualitative criteria are depicted from the least desirable value (appearing in **bold**) to the most desirable value (depicted in ***bold italics***). It is not necessary to provide an order for the value domains, but doing

Criteria tree	Description	Original value domain
Evaluation	Final evaluation	**Unacc.,** Acc., Good, ***Excel.***
Customer	Customer assessment	**Unacc.,** Acc., Good, ***Excel.***
Risk	Risk business assessment	**High,** Med., ***Low***
Shareholder	Shareholders structure	**Private,** Mixed, ***Public***
Payment habits	Customer ability to pay	**Defaulting,** Irregular, ***Regular***
Risk assessment	The assessment of the risk	**High,** Med., ***Low***
Size class	Customer size class	**Unacc.,** Acc., Good, ***Excel.***
Enterprise size	Company size category	**Micro,** Small, Med., ***Large***
Employees	Assessment of properly trained employees	**Unacc.,** Acc., Good, ***Excel.***
Number (a)	Nbr. of assigned employees - qual.	**Small** Med. ***Large***
Number (1)	Nbr. of assigned employees - quant.	**0** – ***25*** [people]
Structure	Educational structure of employees	**Unacc.,** Good, ***Excel.***
Availability (a)	Working hours per week - qual.	**None** Small, Med. ***Large***
Availability (1)	Working hours per week - quant.	**0** – ***40*** [hour]
Investment	Investment assessment	**Unacc.,** Acc., Good, ***Excel.***
Performance	Performance assessment	**Unacc.,** Good, ***Excel.***
Contract model	Type of contract model	**Purchase,** Installation, ***Optimisation***
Contractor	Contractor structure	**Subcontr.,** Mixed, ***Own***
Deadline (a)	Project deadline - qual.	**Short,** Middle, ***Good***
Deadline (1)	Project deadline - quant.	**0** - ***60*** [months]
Finance	Financial construction assessment	**Unacc.,** Acc., Good, ***Excel.***
Funding	Available funding sources	**Credit,** Fee, ***Cohesion***
Bank guarantee (a)	Size of bank guarantee - qual.	**High,** Med., ***Low***
Bank guarantee (1)	Size of bank guarantee - quant.	**1000** - ***0*** [monetary unit]
Profitability	Expected profitability	**Unacc.,** Acc., Good, ***Excel.***
Effectiveness (a)	Effectiveness criteria - qual.	**Low,** Med., ***High***
Effectiveness (1)	Effectiveness criteria - quant.	**0** – ***100*** [points]
Excellence (a)	Excellence criteria - qual.	**Low,** Med., ***High***
Excellence (1)	Excellence criteria - quant.	**0** – ***100*** [points]
Strat.importance	Strategic importance evaluation	**Low,** Med., ***High***
Internal	Strategic importance for the operator	**Low,** Med., ***High***
Buyer	Buyer type	**Existing,** New cust., ***New market***
Collaboration	Collaboration type	**Purchase only,** Short-term, ***Long-term***
New research	Developing new services	**None,** Partial, ***New study***
External	Strategic importance for the purchaser	**Low,** Med., ***High***
Spare capacity (a)	Avail. water after losses and consumption - qual.	**High,** Med., ***Low***
Spare capacity (1)	Avail. water after losses and consumption -quant.	**50** – ***0*** [%]
User growth trend	The growth rate of the water customers	**No,** Small, **Large**
Data	Adequacy of data	**0** – ***100*** [points]
GIS	Adequacy and quality of GIS	**0** – ***100*** [points]
Process data	Adequacy and quality of process data	**0** – ***100*** [points]
Operation data	Adequacy and quality of operation data	**0** – ***100*** [points]
Sales data	Adequacy and quality of sales data	**0** – ***100*** [points]
Customer profiles	Adequacy and quality of customer profiles	**0** – ***100*** [points]

Legend: Unacc. - Unacceptable, Acc. - Acceptable, Excel. - Excellence, Med. - Medium, New cust. - New customer, Subcontr. - Subcontractor, Nbr. – number, Qual. – qualitative, Quant. – quantitative, Avail. – available

1 Quantitative criteria

a Qualitative criteria

a/1 Mapping of quantitive value domains from one criterion into qualitative value domains of another criterion

Fig. 6 Criteria tree with definitions and value domains

so improves the understanding of the decision-making model and makes it easier to define utility functions (Bohanec et al. 2013; Bohanec 2015).

3.1 Evaluation of decision variants

We chose to evaluate four decision variants, that is, four possible projects of the operator, namely, P1, P2, P3, and P4. We assessed them according to the basic criteria in

Table 1 Evaluation of projects P1, P2, P3, and P4 by the basic criteria

Criterion	P1	P2	P3	P4
Shareholders	***Public***	***Public***	***Public***	***Public***
Payment habits	***Regular***	***Regular***	***Regular***	***Regular***
Risk assessment	Med.	Med.	***Low***	Med.
Enterprise size	Med.	Med.	***Large***	Med.
Number (1)	3	1	8	3
Structure	Good	***Excel.***	***Excel.***	***Excel.***
Availability (1)	5	9	24	8
Contract model	Installation	***Optimisation***	Installation	***Optimisation***
Contractor	Mixed	Mixed	**Subcontr.**	**Own**
Deadline (1)	5	59	24	6
Funding	***Cohesion***	Fee	**Credit**	Fee
Bank guarantee (1)	675	803	471	99
Effectiveness (1)	60	54	66	78
Excellence (1)	35	25	37	38
Buyer	New cust.	***New market***	***New market***	New cust.
Collaboration	Short-term	***Long-term***	***Long-term***	Short-term
New research	Partial	***New study***	**None**	***New study***
Spare capacity (1)	25	8	47	15
User growth trend	**No**	***Large***	***Large***	***Large***
GIS	75	80	65	95
Operation data	94	95	85	97
Sales data	91	88	75	93
Customer profiles	80	80	70	90

the criteria tree (Table 1). We marked the least and the most desirable value domains for the qualitative criteria in **bold** and ***bold italics***, respectively, depending on the defined value domain for each individual criterion. The first step in the final evaluation involves evaluating each project using the basic criteria. Then, the calculation is conducted starting with the criteria that appear lower in the criteria tree, that is, towards the root of the tree.

The decision-making model along with the user interface and all necessary functions and algorithms implemented in C# programming language was implemented as an IT artefact (application). All weights, utility function, decision rules, evaluations, etc. are stored in a database, and are a part of the operator's Knowledge Management System. The final results are shown in the evaluation table (Table 2).

The decision-making model can calculate the values of the superior criteria using the aggregation utility functions. The result is the final evaluation of each project. The advantages of the presented decision-making model include the use of both quantitative and qualitative criteria. A quantitative criterion that is to be aggregated with qualitative criteria is not converted into a qualitative criterion, but an additional qualitative

Table 2 Final evaluations of projects using the aggregated criteria

Criteria	P1	P2	P3	P4
Evaluation	Good [0.72,0.80]	***Excel.*** [0.60,0.70]	V.Good [0.65,0.73]	***Excel.*** [0.72,0.82]
Customer	***Excel.*** [0.45,0.72]	***Excel.*** [0.47,0.74]	***Excel.*** [0.72,1.00]	***Excel.*** [0.48,0.75]
Risk	***Low*** [0.35,0.90]	***Low*** [0.35,0.90]	***Low*** [0.46,1.00]	***Low*** [0.35,0.90]
Size class	Good [0.51,0.69]	Good [0.63,0.80]	***Excel.*** [0.66,0.88]	Good [0.65,0.83]
Employees	Good [0.18,0.37]	Good [0.40,0.60]	***Excel.*** [0.42,0.74]	Good [0.45,0.65]
Investment	Acc. [0.33,0.54]	***Excel.*** [0.37,0.59]	Good [0.42,0.63]	***Excel.*** [0.42,0.62]
Performance	**Unacc.** [0.47,0.85]	***Excel.*** [0.43,0.82]	Good [0.26,0.63]	Good [0.50,0.87]
Finance	Good [0.24,0.65]	Good [0.18,0.59]	Good [0.57,0.98]	***Excel.*** [0.43,0.83]
Profitability	47.50 [Good]	39.50 [Good]	51.50 [***Excel.***]	58.00 [***Excel.***]
Strat. importance	**Low** [0.48,0.71]	***High*** [0.58,0.86]	Med. [0.43,0.66]	Med. [0.66,0.88]
Internal	Med. [0.30,0.86]	***High*** [0.48,1.00]	***High*** [0.13,0.66]	***High*** [0.13,0.65]
External	**Low** [0.45,0.73]	***High*** [0.38,0.68]	Med. [0.05,0.33]	Med. [0.64,0.91]
Data	78.06 [Good]	81.98 [***Excel.***]	67.8 [Good]	94.88 [***Excel.***]
Process data	90.3	89.9	67.8	94.88

Bold indicates the least desirable value domains
Bolditalics indicates the most desirable value domains

criterion is added to the model instead; therefore, we retain the original quantitative value in addition to the newly obtained qualitative value. This allows us to distinguish between projects that may have the same final qualitative score (Table 2).

For every qualitative aggregation function, the result consists of a qualitative value and numeric interval that describes that project more precisely than a single qualitative value. The interval defines the position of the project inside the calculated qualitative value. Each qualitative value is described by an interval from 0 to 1, where 0 represents the least desired value and 1 represents the most desired value within the qualitative value. Qualitative values are not a reliable indicator of the merit of a project. This uncertainty implies that the projects could be rated any qualitative value, or if described by a numeric interval, they could be ranked anywhere in the interval from 0 to 1. In the proposed design, all superior criteria are assigned a quantitative value to position them more precisely within the quantitative interval that corresponds to their qualitative value. We have defined the domain transformation functions for the quantitative criteria that are converted into qualitative criteria. Their qualitative values are shown in brackets following a quantitative value that was calculated prior to the transformation (Table 2).

4 Discussion

The discussion is divided into contribution to applied knowledge (presented in Sect. 4.1) and contribution to science (presented in Sect. 4.2) to highlight the advantages of the novel hybrid multi-criteria decision method. In Sect. 4.3, we discuss the strengths and weaknesses of the proposed method.

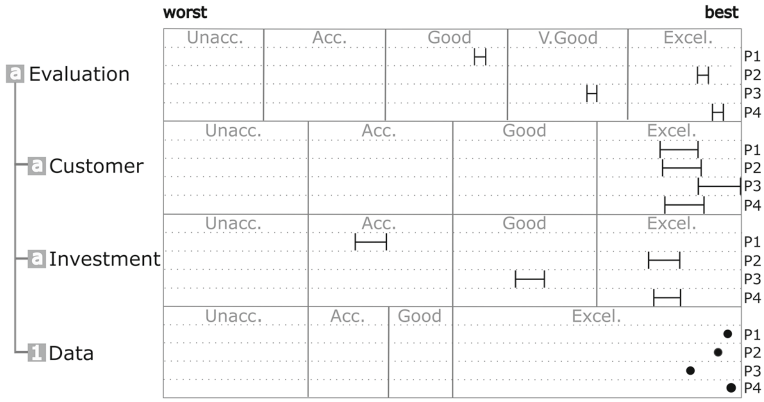


Fig. 7 Graphical representation of projects ranked by the selected criteria

4.1 Contribution to applied knowledge

The final evaluation reveals that the project P1 is qualitatively evaluated as 'Good', which is the lowest grade among the evaluated projects. P3 is graded one level higher as 'V.Good'. P2 and P4 are both rated the same (**Excel.**) even though there are differences between these two projects. This lack of distinction is a common problem with the DEX method and with qualitative evaluation in general. Given that the proposed decision-making model provides original quantitative assessments for some basic criteria, we can then compare P2 and P4 by their criteria values from the quantitative assessments. From the final evaluation in Table 2, it is clear that project P2 is rated worse than P4, as its quantitative assessment varies in the interval from 0.60 to 0.70. The quantitative assessment of project P4 varies in the interval from 0.72 to 0.82 and therefore it was selected for further consideration for implementation by the operator's experts.

The operator's experts also analysed other criteria and discovered differences that have a considerable impact on the final decision. Using Fig. 7, below, we helped decision makers to understand the differences between the projects and the reasons for their final evaluations. The operator's experts found this ability of the decision-making model to explain the evaluations to be the most important advantage of the proposed decision-making method.

The use of the quantitative and qualitative criteria in the same decision-making model helped us to improve the predictive power of the decision-making model, as we could assess the projects using the natural values of their criteria. The advantage of the proposed decision-making method over MAUT is that we can utilise the qualitative criteria in the decision-making model even if we do not have precise criteria values, but only estimates, i.e., value intervals. These value intervals may be narrower than the interval obtained by converting a single qualitative value into an equivalent quantitative interval. Quantitative methods tend to be preferred over qualitative methods, allowing us to distinguish between projects that may be otherwise evaluated with the same final qualitative value. Combining the quantitative and qualitative criteria in the same decision-making model allows us to keep the intrinsic values of criteria and are thus able to see even small differences between the projects up to the final evaluation. The ability to conduct quantitative and qualitative evaluations for an individual criterion presents new options in the analyses, the examples of which are presented in Fig. 7 below.

Figure 7 presents the quantitative and qualitative values, which are denoted via points and intervals extending from the minimal to the maximal value (seen as lines), respectively. The figure presents the final evaluation and its direct sub-criteria. Similar visualisations can be used to explain any aggregate criterion in the decision-making model.

4.2 Contribution to science

The DEX method was used to allow the evaluation of criteria with imprecise or missing criteria values and take advantage of its transparency and simple *if–then* decision rules, given that it is easier for experts to understand than the MAUT method (Žnidaršič et al. 2008; Bohanec et al. 2013; Bohanec et al. 2017). A disadvantage of the DEX method and qualitative methods in general is the low resolution of the criteria scales, which requires the user to group similar options into domains. This results in a loss of precision, which often leads to difficulties in differentiating the final rank of variants. To tackle this issue, the MAUT method is used for the quantitative criteria and for calculating the final ranks of the variants.

As indicated in the literature section, many potential combinations of two or more individual MCDMs exist, and numerous HMCDM approaches in different fields of application have been described in recent literature; therefore, a comprehensive comparison of the advantages and disadvantages of the presented and existing HMCDMs is not feasible. Furthermore, no method can be considered as "best" either for a general or for a particular problem, and the selection of individual MCDMs should be adapted to the decision problem at hand (Zavadskas et al. 2016).

We have followed the recommendations outlined by Zavadskas et al. (2016), and have considered the nature of the decision problem and selected individual MCDMs that are suited to quantitative criteria with precise values (MAUT) and to qualitative criteria or quantitative criteria with poorly defined or uncertain values (DEX). Furthermore, we have fully integrated the results of criteria evaluation using the individual MCDMs by developing a software artefact that seamlessly integrates both MCDMs (DEX and MAUT). As illustrated in Figs. 6 and 7, the proposed method allows us to transform quantitative criteria into qualitative and thereby allowing us to simultaneously conduct quantitative and qualitative evaluation of a criterion, which greatly improves the model transparency, flexibility, and accuracy.

4.3 Strengths and weaknesses of novel hybrid multi-criteria decision method

The aim of this section is to summarise and discuss the strengths and weaknesses of the presented novel MCDM method. The methods main strength is the possibility to utilize qualitative and quantitative criteria in the same model and perform both qualitative and quantitative evaluation of the decision tree, while allowing the decision makers to see the original values of criteria. This way we avoid the loss of precision which would occur if the original values of quantitative criteria were lost in conversion to qualitative criteria, and allow the decision experts to observe small differences between decision variants that may have the same final qualitative score. Furthermore, the use of both types of criteria gives decision experts more flexibility in expressing the evaluation results and greater comprehensibility of the qualitative method while maintaining the precision of a quantitative method. Decision experts can use the easy to understand weighted sum utility function for the quantitative criteria and *if–then* rules for the qualitative criteria. Use of the method results in an easy to understand decision model, which is transparent, flexible, consistent, and accurate, and which reduces the time required to reach a decision. The ability to conduct quantitative and qualitative evaluations for an individual criterion in parallel presents new options for decision analysis.

Weaknesses of the presented method are that the value domains for qualitative criteria must be well defined, i.e., they must be ordered from the least to the most desirable value. This requirement improves the understanding of the decision-making model and makes it easier to define the utility functions, but requires additional work. Currently, the proposed method supports a limited set of transformation functions from quantitative to qualitative criteria, and further development and testing of additional transformation functions is planned. The method is also relatively complex owing to its hybrid nature and criteria domain transformation functions. However, a user-friendly software implementation can hide the complexity from the end-users.

5 Conclusion

We have developed a novel HMCDM by integrating the criteria value domains of quantitative (MAUT) and qualitative (DEX) methods in the same decision-making model, and implemented it in a real-world case. The problem addressed in the implementation case is a multi-criteria decision problem, which is a part of the evaluation of economic feasibility of water supply system projects. The goal of the developed decision-making model is to facilitate knowledge management and decision making by enabling a structured, formal decision-making process with a defined set of criteria and weights, thus reducing the time required to reach a decision, improving decision quality and consistency, and increasing transparency in the operator's choice of investment projects.

The decision-making model was used to evaluate the variants, i.e., potential investment projects according to their characteristics. Using the proposed decision-making model, we were able to conduct parallel quantitative and qualitative evaluations of the investment projects as decision variants. The transparency of the decision-making model structure and its easily understandable utility functions allow the decision-maker to comprehend the final result at a glance.

The decision-making model offers new possibilities, as it allows the operator's experts to gain a better understanding of the decision problem and evaluate projects according to the individual criteria. The results of the analyses allowed the decision makers to analytically perceive the differences between the projects, and consequently make more informed decisions. The decision-making model was implemented as a software artefact containing the formal representation of the operator's decision criteria based on long-term experiences and expertise, and will be a part of the operator's Knowledge Management System.

The presented novel HMCDM is expected to be applicable to similar decision problems, where a transparent integration of qualitative and quantitative criteria would be beneficial. The advantage of the presented approach is its potential of making the decision makers aware of small but influential differences between the decision variants. As noted by Zavadskas et al. (2016), the use of HMCDM in water management problems is not well established; therefore, we hope our research will contribute to the development of MCDM and its application in this field.

In addition to water supply systems, the operator is also engaged in the fields of district energy, efficient lighting, and energy management. Therefore, we will further develop decision-making models and test it in these fields. A planned future research direction is to construct and test a decision model that would implement the input and calculation of numerical values with uncertainty intervals.

Instead of linear functions, we could use logarithmic, exponential, polynomic, or other functions with minor adaptations of the transformation functions, provided they satisfy the conditions of being continuous, differentiable, and monotonically rising. We also plan to develop new analyses, which will simultaneously visualise both quantitative and qualitative criteria and will help decision makers to better understand the decision process because of the large set of information available to them.

We also intend to integrate the presented novel hybrid MCDM with the operator's IoT/OT (Internet of things/Operational Technology) platform, which captures considerable energy consumption data close to real time. In this way, we could improve the optimisation of energy consumption and reduce the environmental impact of projects.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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