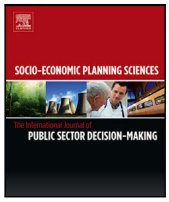
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A multiple criteria methodology for priority based portfolio selection

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ABSTRACT

This paper presents a new methodology combining multiple criteria sorting or ranking methods with a project portfolio selection procedure. The multicriteria method permits the comparison of projects in terms of their priority based on qualitative and quantitative criteria. Then, a feasible set of projects, i.e. a portfolio, is selected according to the priority defined by the multiple criteria method and satisfying a set of resources and logical constraints. The proposed portfolio selection methodology is called Priority Based Portfolio Selection (PBPS) and can be applied in different contexts. We present an application in the urban planning domain where our approach allows us to select a set of urban projects based on their priority, budgetary constraints, and urban policy requirements. Given the increasing interest of historical cities to reuse their cultural heritage, we applied and tested our methodology in this context. In particular, we show how the methodology can support the prioritization of the interventions on buildings with some historical value in the historic city center of Naples (Italy), taking into account several points of view.

1. Introduction

Portfolio decision analysis (PDA) handles selecting a set of projects that optimize some objectives subject to several constraints and not exceeding the available budget [1]. PDA has many applications in several contexts ranging from selecting research and development projects in the energy domains [2] to choosing environmental management decisions [3].

Many methodologies have been proposed for the portfolio selection problem. Nonetheless, the primary approach [4] assigns a value function to all the projects based on their evaluations on a set of criteria. Then, the portfolio that maximizes the sum of the values of all the included projects is selected.

In this paper, we consider the case in which the decision maker (DM) wants to select the projects for the portfolio based on a previous prioritization which is a rather general procedure in the current operational practice [see e.g.,5,6]. For this reason, we call the approach we propose the Priority-Based Portfolio Selection methodology (PBPS). PBPS is based on a preference relation on portfolios built upon a preference relation on projects that we call priority. The fundamental difference between PBPS and the classical PDA approach is that we consider only the preference order of projects without considering the value assigned to them. To do this, we use ordinal priorities rather than the cardinal utilities adopted in the classical approach. The theoretical foundation of the basic idea of PBPS, that is, ranking sets of objects (i.e. portfolios) based on the preference for the objects (i.e. projects), has been primarily studied in economics [7].

PBPS consists of two steps. In the first step, a Multiple Criteria Decision Aiding (MCDA) method [see e.g.,8] is used to define a priority relation on the set of projects. In the second step, an optimization procedure selects the portfolio with the highest priority projects, considering some constraints related to the available budget and specific requirements, such as selecting a minimal number of projects with specified characteristics.

Due to its peculiarities, adopting PBPS is very beneficial in urban planning. Nowadays, cities are critical actors in accomplishing targets of strategic and global importance, such as achieving sustainable development [9]. Therefore, cities need to improve the use of resources, enhancing their innovation capacity and becoming resilient and sustainable systems [10]. Thus, urban policies must be able to pursue at the same time several objectives. These objectives are both of economic nature [e.g.,11] and of non-economic nature [12]. In addition to that, policies need to be sustainable and deal with improving the environment and the urban landscape [13].

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Moreover, the definition of urban policies has to consider some significant restrictions, such as the current reduction of public expenditures or emergencies. In this context, the definition of urban policies needs a more systemic and holistic approach in planning [14], and it has to focus on the management and optimization of available resources [15].

Consequently, in such an increasingly complex urban context [16], it is necessary to develop decision-aiding methodologies for defining urban policies that are:

- More accurate, specific, and selective about characterizing the potential actions [17].
- More flexible, adaptive, and robust regarding their implementation [18].
- More pluralist and participatory concerning the involvement of the stakeholders [19].

Indeed, our PBPS methodology satisfies the listed requirements through a decision procedure characterized by the following main points:

- The characterization of the potential projects through a priority relation obtained with an MCDA procedure that accurately takes into account all the criteria and heterogeneous points of view of the specific urban planning policy.
- The selection of integrated sets of projects as part of a comprehensive strategy to be evaluated in its totality. The whole portfolio of projects to implement is restricted by constraints that can be flexibly adapted to the changing conditions in the definition of urban planning policies.
- The involvement of various stakeholders to elicit preference parameters of the MCDA method and react to the portfolio selection procedure results. This way, the requirements from a plurality of participants can be iteratively included in the urban policy-making process.

To show how PBPS can support urban planning decisions, we apply it to a case study related to cultural heritage reuse in the historical city of Naples (Italy), listed among the UNESCO World Heritage sites since 1995. Defining the reuse of cultural sites is a highly complex task that generates multiple impacts when developing a sustainable urban environment. Therefore, the mere economic aspect of the problem needs to be integrated with several criteria related to very different aspects, often intangible and difficult to quantify. The government of the city of Naples, in 2011, approved a management plan for this area, identifying objectives and projects to be implemented to preserve, reuse and enhance its cultural heritage [20]. However, the plan fails to indicate which projects should be prioritized and which are the most beneficial for addressing the strategic objectives defined. Unfortunately, when there is an increasing need for rationalizing expenses and resources, it is unrealistic to think that all the projects will be funded or will be funded altogether. Therefore, it is necessary to select only some projects from the plan.

This paper is organized as follows. In Section 2 we briefly review how multicriteria approaches have been adopted for the definition of portfolios, emphasizing the urban context. In Section 3, we detail the PBPS methodology. In Section 4 we present the main elements of our case study. In Section 5 we describe the implementation of the selected MCDA method for the case study, while in Section 6 we describe the results obtained for the selection process. Lastly, Section 7, concludes the paper.

2. Literature review

PDA approaches help DMs to make informed decisions. Such approaches have been implemented in several contexts, e.g., from the location of wind farms [21] to the selection of research and development projects [e.g.,22]. Moreover, adopting such an approach allows the definition of a strategy that does not consider only one project but the whole portfolio of projects.

Recently, [23] have reviewed the latest developments in PDA highlighting, among the several insights, how portfolio problems are usually addressed from a multicriteria perspective [e.g.,24]. Then, several approaches can be defined to find the preferred portfolio. The most common one is using multi-attribute utility theory [e.g.,25], where a value for each project on each criterion is assigned, and the utility of the portfolio consists in the utility of all the projects that made the portfolio. Alternatively, the use of AHP or ANP [e.g.,26] and the use of outranking methods such as PROMETHEE methods [e.g.,27] can support the sorting or the ranking of a set of projects. In addition, Data Envelopment Analysis [e.g.,28] or scoring templates [e.g.,29] are also adopted to define which projects are the most beneficial ones. Besides, other modelling aspects can be considered, such as uncertainty for the evaluation of the performances of the projects [e.g.,30], interaction with the stakeholders [e.g.,31], risk-averse preferences [e.g.,32] and robustness of the portfolios [e.g.,33].

Nevertheless, independently from the particular approach proposed, the main aim for organizations is to propose a prioritization of the projects that include the appraisal of the projects and the construction of the portfolio itself [34]. Indeed, according to [35] it is essential that organizations, in the first place, categorize the projects; following that, and based on this categorization, they assign a priority to each project.

In this sense, a significant example is provided by the internationally recognized consultancy company “McKinsey & Company" in their technical report [36]. In the first step, they suggest ranking projects based on metrics such as net present values and the easiness of implementation. In the second step, they advice assigning each project into tiers to identify the highest priority projects. Then, the management can select a portfolio of projects based on those priorities and according to their capacity and capability. However, they do not specify which techniques should be applied for each step.

Some attempts to prioritize projects and then select portfolios have been proposed. For example, [37] determines, thanks to the use of ANP and DEMATEL, a priority index for prioritizing a portfolio of potential investments followed by selecting a portfolio of projects without specifying how the selection process should be conducted. Similarly, [38] combined a PROMETHEE method with three integer programming formulations that maximize the scores obtained by the MCDA approach, the average of the scores, and a parametric solution on the number of companies selected, respectively. They aimed to select a subset of applications made by private companies applying for public funding. Also,[39] adopted a PROMETHEE method and defined optimal portfolios based on the number of projects included in the portfolio. Another example is reported in [40] where portfolios are selected after ordering the projects based on probabilistic economic return, budget available and priorities of the projects. Unfortunately, the authors do not provide any formulations of the models used in both steps. Finally, [41] applied a knapsack approach based on the priority classes obtained by an AHP-K Means algorithm. Although they proposed the two steps approach, they did not formulate a proper portfolio problem, and their method was particular to the peculiar application proposed.

Although many organizations can benefit from such an approach [42], prioritizing projects is extremely important when dealing with urban policies [43] and, in particular, in the context of the cultural heritage [44].

Regrettably, when dealing with urban policies in the literature, the decisions are not concerning the whole portfolio but focus only on ranking or sorting urban projects. Usually, many criteria are adopted [45] and several ranking or sorting MCDA methods are adopted to support the decision process in the urban context such as AHP [46, i.e], ELECTRE methods [47, i.e] and PROMETHEE methods [48, i.e]. Moreover, peculiar approaches are developed according to the specific application’s needs, except for the work of [49], who proposed an

integrated framework involving MCDA methods for evaluating complex urban systems.

Instead, only some attempts have been provided that involve selecting a whole set of projects to be defined altogether, taking into account the effects of the whole portfolio on the different objectives. In this sense, [50] integrates a PROMETHEE Method with a genetic algorithm proposing a framework for selecting sustainable urban development projects. Analogously, [3] proposes a general framework for selecting projects in environmental management. Furthermore, [51] models the investment selection of historic buildings as a knapsack problem with several criteria adopting a weighted sum criteria approach to choose the best portfolio.

3. The priority based methodology for portfolio selection

The PBPS methodology is based on integrating a portfolio decision problem with a ranking or a sorting procedure. In the following, we describe the methodology detailing how we define the priority relation among portfolios and how MCDA methods can be embedded in PBPS.

3.1. Defining a priority relation among portfolios

We have a set $A = \{a_1, \dots, a_n\}$ of projects and a relation $\succsim$ on A such that for all $a_i, a_{i'} \in A$, $a_i \succsim a_{i'}$ means that project a_i has a priority not smaller than $a_{i'}$. It is supposed that $\succsim$ is a preorder, i.e. it is reflexive and transitive but not necessarily complete. We shall denote by $\succ$, $\sim$ and $\bowtie$ the preference (asymmetric part of $\succsim$), the indifference (symmetric part of $\succsim$) and the incomparability, respectively, in the preorder $\succsim$, that is, for all $a_i, a_{i'} \in A$

- $a_i \succ a_{i'}$ if $a_i \succsim a_{i'}$ and not $a_{i'} \succsim a_i$,
- $a_i \sim a_{i'}$ if $a_i \succsim a_{i'}$ and $a_{i'} \succsim a_i$,
- $a_i \bowtie a_{i'}$ if not $a_i \succsim a_{i'}$ and not $a_{i'} \succsim a_i$.

A portfolio P is a set of projects, that is $P \subseteq A$, with the powerset 2^A of A being the set of all potential portfolios. In general, there is a set C of constraints to be satisfied by the portfolio, such as budget constraints. A portfolio is defined as feasible if it satisfies all the constraints from C. The set of all feasible portfolios is denoted by $\mathcal{P} \subseteq 2^A$. In PBPS, we select as many projects with the highest priority as long as the portfolio is feasible. Then, as many with the second highest priority as long as the portfolio is feasible until we explored all the priority levels. In this perspective, the formal definition of the *priority based portfolio selection* can be given as follows.

If the priority $\succsim$ is a complete order,[1] it is straightforward to determine the solution for the PBPS. Indeed, we can reorder the elements of each potential portfolio $B = \{b_1, \dots, b_h\} \subseteq A$ based on the priority $\succsim$, so that $b_{\succsim(1)}$ is the highest priority project from B, $b_{\succsim(2)}$ is the second highest priority project from B, and so on, until $b_{\succsim(h)}$ being the least priority project from B. Given potential portfolios $B, C \subseteq A$, $B \neq C$, $B \neq \emptyset$, $C \neq \emptyset$ and considering a priority relation $\succsim$ being a complete order on A, we say that portfolio B is priority preferred to portfolio C, denoted by $B \succsim^* C$, if one of the three following conditions is satisfied

lex0 $b_{\succsim(t)} = c_{\succsim(t)}$ for $t = 1, \dots, |B| = |C|$

lex1 there exists $k = 1, \dots, |B|-1$ such that $b_{\succsim(t)} = c_{\succsim(t)}$ for $t = 1, \dots, k-1$ and $b_{\succsim(k)} \succ c_{\succsim(k)}$,

lex2 $b_{\succsim(t)} = c_{\succsim(t)}$ for $t = 1, \dots, |C|$ and $|B| > |C|$.

[1] Let us remember that a complete order R on a set X is a binary relation strongly complete (that is xRy or yRx for all $x, y \in X$), transitive and antisymmetric (if xRy and yRx, then $x = y$ for all $x, y \in X$). A complete order sorts the elements of a set X one after the other without ex aequo and incomparability, i.e., a complete order is a preorder presenting neither ex aequo nor incomparability cases.

Condition **lex 0** states that if two portfolios are made of the same number of projects of the same priority, they are equivalent with respect to the portfolio priority preference $\succsim^*$. Condition **lex1** states that if the first $k-1$ projects in portfolios B and C are characterized by the same priority levels and the kth project of B has a higher priority than the kth project of C, then B is preferred to C. Condition **lex2** states that if all the projects from portfolio C are also included in portfolio B, but B includes at least one more additional project, then B is preferred to C. The priority order $\succsim^*$ corresponds to the leximax ordering introduced in [52].

If the priority relation $\succsim$ is a complete order, then the preference relation $\succsim^*$ is a complete order on the set of potential portfolios 2^A, and, consequently, on the set of feasible portfolios $\mathcal{P}$. Therefore, one portfolio is preferred to all other portfolios from $\mathcal{P}$, which, consequently, is the solution of the PBPS.

Despite its definition's simplicity, finding the solution of PBPS in real-world problems can become very complex in case of a large number of available projects and the presence of constraints C. Thus a combinatorial optimization problem must be adopted to find the solution to the PBPS. It can be formulated as a $0-1$ knapsack problem with constraints C. More precisely, reordering the projects from A in the priority order, so that $a_i \succsim a_{i'}$ if $i \geq i'$, we can associate a $0-1$ decision variable, x_i, to each $a_i \in A$, such that $x_i = 1$ if a_i is selected, and $x_i = 0$, otherwise. The priority based portfolio to be selected is the optimal solution of the following problem K1:

$$\max f(x) = \sum_{\{i \,:\, a_i \in A\}} c_i x_i,$$

subject to the constraints C, with

$$c_i = \begin{cases} 1 & \text{for} \quad i = 1, \\ \sum_{k=1}^{i-1} c_k + 1 & \text{for} \quad i = 2, \dots, n, \end{cases}$$

that is, $c_i = 2^{i-1}$. The idea is that the coefficient c_i of a project a_i should be strictly larger than the sum of all the coefficients c_k associated with all the projects $a_k, k = 1, \dots, i-1$, having a lower priority. Therefore, for each $a_i \in A$, the contribution c_i to the objective function $f(x)$ is greater than the contribution $\sum_{\{a_k \in A, k<i\}} c_k$ of all $a_k \in A$ with smaller priority, that is $i > k$.

Let us now consider a more complex case in which the priority relation $\succsim$ is a preorder, so that there can be cases of ex aequo, i.e., $a_i, a_{i'} \in A$ with $a_i \neq a_{i'}$ such that $a_i \sim a_{i'}$, and cases of incomparability, i.e. $a_i, a_{i'} \in A$ with $a_i \neq a_{i'}$ such that neither $a_i \succsim a_{i'}$ nor $a_{i'} \succsim a_{i'}$. In this case, PBPS can be formulated as follows.

A complete order R on the set of projects A is *compatible* with the priority $\succsim$ if for all $a_i, a_{i'} \in A$

$$a_i R a_{i'} \Rightarrow a_i \succsim a_{i'} \text{ or } a_i \bowtie a_{i'}$$

Therefore a complete order R is compatible with the priority $\succsim$ if it orders the projects from A without any inversion concerning the priority, that is, there must not exist $a_i, a_{i'} \in A, a_i \neq a_{i'}$ such that $a_i \succ a_{i'}$, but $a_{i'} R a_i$. Let us observe that if $\succsim$ is not a complete order, multiple compatible complete orders exist.

Given the set $\mathcal{P}$ of feasible portfolios and a priority relation $\succsim$, we say that $B \in \mathcal{P}$ is one solution of the priority based portfolio selection problem if at least one complete order $\succsim_q$ compatible with $\succsim$ such that $B \succsim_q^* C$ for all $C \in \mathcal{P}$ exists. In simple words, since there are a plurality of complete orders $\succsim_q$ compatible with the preorder $\succsim$ and since there is no a priori reason to consider one compatible order $\succsim_q$ more reliable than another, we have to accept as solutions of the PBPS problem based on $\succsim$ all the solutions of the analogous problem related to the compatible complete orders $\succsim_q$. Observe that the same solution can be obtained by more than one compatible order $\succsim_q$. In general, all the obtained solutions or, at least a set of representative solutions have

to be discussed with the decision maker to select one of them, which will become the definitive project portfolio.

The PBPS problem related to a priority relation $\succsim$ being a preorder[2] can be handled by applying the knapsack problem K1 to all complete compatible orders $\succsim_q$ compatible with the priority relation $\succsim$. However, computing all compatible orders $\succsim_q$, could be a non-trivial problem for large instances. In case the priority relation $\succsim$ is a complete preorder[3] a much simpler and effective way to handle the problem is through the reformulation of problem K1 obtained as follows. Let us define by C_h, $h = 1, \dots, q$, the equivalence classes of the priority relation $\succsim$ that is, the sets of elements being indifferent with respect to $\sim$, i.e. the set of elements characterized by the same priority. The classes are ordered from the one with the highest priority to the one with the lowest priority. This means that for $a_i, a_{i'} \in A$

- if $a_i \in C_h$, $a_{i'} \in C_{h'}$ and $h > h'$, then $a_i \succ a_{i'}$,
- if $a_i, a_{i'} \in C_h$, then $a_i \sim a_{i'}$.

Taking into account the partition of A in equivalence classes $C_h, h = 1, \dots, q$, the priority based portfolio to be selected is the optimal solution for the following problem K2:

$$\max f(x) = \sum_{\{i\,:\,a_i \in A\}} c_i x_i,$$

subject to the constraints C, where $c_i = \gamma_h$ if $a_i \in C_h$, with

$$\gamma_h = \begin{cases} 1 & \text{for} \quad h = 1, \\ \sum_{k=1}^{h-1} \gamma_k |C_k| + 1 & \text{for} \quad h = 2, \dots, q. \end{cases}$$

The idea is that the coefficient γ_h, being equal to the contribution c_i to the objective function $f(x)$ of projects a_i from equivalence class $C_h, h = 1, \dots, q$, is greater than the contributions

$$\sum_{\{a_{i'} \in C_k, k<h\}} c_k = \sum_{k=1}^{h-1} \gamma_k |C_k|$$

of all $a_{i'} \in C_k$ with $k < h$. In other words, for all $a_i \in A$, a portfolio including only a_i assigns to $f(x)$ a greater value than a portfolio including all the projects with smaller priority. With the proposed procedure, projects with the highest priority are selected first, unless this is impossible due to the constraints. In that case, the optimization process considers projects of the next lower priority level until it reaches the projects in the lowest level.

As we have already observed, there can be a plurality of solutions, in fact, one for each complete order $\succsim_q$ compatible with the priority relation $\succsim$, with the caveat that some of these solutions can be equal. Nonetheless, in general, there is no a priori reason to prefer one solution to another one [53], so the selection of one portfolio among all those pluralities of solutions requires an interaction with the stakeholders.

The knapsack optimization problem K2 can be used also in case $\succsim$ is a preorder with some cases of incomparability, proceeding as follows. Analogously to what happens for complete orders, a complete preorder R on the set of projects A is *compatible* with the priority $\succsim$ if for all $a_i, a_{i'} \in A$

$$a_i R a_{i'} \Rightarrow a_i \succsim a_{i'} \text{ or} a_i \bowtie a_{i'}$$

Any preorder $\succsim$ can be expressed as the intersection of all its compatible preorders R [54]. Consequently, once all the complete preorders compatible with the priority relation $\succsim$ are determined, the knapsack optimization K2 can be applied to each of these complete preorders obtaining all the solutions. Moreover, applying K2 to all complete preorders compatible with $\succsim$ is more convenient than applying K1 to all complete orders compatible with $\succsim$, because the compatible complete preorders are generally less than the compatible orders. Let us observe that there are several algorithms to compute the whole set of complete orders R compatible with a preorder $\succsim$, technically called linear extensions [see e.g.,55]. Moreover, since the number of linear extensions can be very large, some algorithms to obtain a uniform random sample have been proposed [see e.g.,56].

3.2. MCDA methods for the PBPS methodology

The priority relation $\succsim$ can be obtained by adopting different procedures; among them, we look at the MCDA methods for their capacity to deal with multiple criteria and represent multiple stakeholders. In the following, we explain how to embed them in the PBPS according to their characteristics:

(1) using some aggregation functions giving an overall numerical evaluation $U(a_i)$ for the priority of projects $a_i \in A$ based on a set of given attributes (for example, using a Multiple Attribute Utility Theory value function [4] or PROMETHEE II outranking method [57]), one can obtain a priority relation $\succsim$ by stating $a_i \succsim a_{i'}$ if $U(a_i) \geq U(a_{i'})$. In this case, the priority relation $\succsim$ is a complete preorder that admits cases of ex aequo but does not admit cases of incomparability. Consequently, after computing all complete compatible orders with the priority relation $\succsim$, the knapsack optimization model K2 can be used in this case.

(2) using an outranking method such as ELECTRE III [58,59] or PROMETHEE I [57], based on a given set of criteria, one can partially rank projects from A obtaining a priority relation $\succsim$ being a preorder that in general admits cases of ex aequo as well as cases of incomparability. Consequently, after computing all complete preorders compatible with the priority relation $\succsim$, knapsack optimization model K2 can be used on each of these compatible complete preorders.

(3) using a sorting procedure such as the pessimistic or optimistic procedure of ELECTRE TRI [59,60] assigning each project to one single class in a set of predefined classes ordered according to the priority of their elements C_q (e.g. $C_1 \equiv$ { low priority projects }, $C_2 \equiv$ { medium priority projects }, $C_3 \equiv$ { high priority projects }). In this case the priority relation $\succsim$ is obtained by stating $a_i \succsim a_{i'}$ if $a_i \in C_h, a_{i'} \in C_{h'}$ and $h \geq h'$. Observe that the classes of the sorting procedure are the equivalence classes of $\succsim$ in the sense that the same priority level characterizes them. In this case, $\succsim$ is a complete preorder; therefore, this case is equivalent to case 1) and, consequently, we can use the knapsack optimization problem K2.

(4) using a sorting procedure assigning each project to an interval of contiguous classes $[C_p, C_{p'}]$ as it is the case with ELECTRE TRI nC [61] one can obtain a preorder by defining the priority relation as follows:

$$a_i \succsim a_{i'} \text{ if } p(i) \geqslant p(i') \text{ and } p'(i) \geqslant p'(i')$$

where $[C_{p(i)}, C_{p'(i)}]$ and $[C_{p(i')}, C_{p'(i')}]$ are the interval of classes to which a_i and $a_{i'}$ are assigned, respectively. Once obtained the priority relation $\succsim$, this case is equivalent to case 2) and one has to proceed as explained at that point. However, observe that in case $p'(i) - p(i) \leq 2$ for all $a_i \in A$ (that is, each action a_i can be assigned to intervals $[C_{p(i')}, C_{p'(i')}]$ of no more than two classes), the priority relation $\succsim$ is a complete preorder ordering the interval $[C_h, C_{h+1}], h = 1, \dots, q-1$, after $[C_h, C_h]$ and before $[C_{h+1}, C_{h+1}]$, that is,

$$[C_1, C_1] \prec [C_1, C_2] \prec [C_2, C_2] \prec \dots [C_h, C_h] \prec [C_h, C_{h+1}] \prec [C_{h+1}, C_{h+1}] \dots$$

$$\dots \prec [C_{q-1}, C_{q-1}] \prec [C_{q-1}, C_q] \prec [C_q, C_q]$$

[2] With possible cases of incomparability and ex aequo.

[3] In case there can be cases of ex aequo but there are not cases of incomparability.

where $[C_h, C_k] \prec [C_{h'}, C_{k'}]$ means that $a_{i'} \succ a_i$ for all $a_i \in [C_{h'}, C_{k'}]$ and $a_{i'} \in [C_h, C_k]$. This case is, therefore equivalent to case 1) and case 3), and consequently, the project portfolio to be selected can be found to solve the knapsack optimization problem K2.

3.3. PBPS steps

The following steps should be pursued to apply the PBPS methodology to real-life applications:

1. *Identification of the problem*. From the analysis of the problem, the following elements should be identified:
   - The stakeholders involved in the decision process, and the criteria, used to assess the performance of the projects.
   - The actions to implement, i.e. the projects that could be implemented and their performances in terms of each criterion.
   - The constraints related to the execution of the projects.
2. *Choice of a method to define the priority relation*. We suggest using a multiple criteria sorting or ranking method in a constructive perspective [62], in which the stakeholders are involved in the building process of the priority relation. Any other assignment methods could also be adopted as, for example, clustering methods [i.e.,63]. Thus, the following elements should be identified:
   - The elicitation of the preference to be used in the interactive process.
   - The parameters to be defined to implement the sorting or the ranking method.
   - The priorities of each project based on the priority relation(s) $\succsim$ achieved as a result of the ranking or the sorting method implemented.
3. *Selection of a portfolio of projects through the knapsack problems K1 or K2*. We define "the preferred portfolio", i.e. a set of projects that should be executed taking into account the different points of view of the stakeholders and the criteria used to assess the projects themselves while satisfying the constraints. The following steps should be implemented:
   - Determine the coefficients c_i for knapsack problem K1 or K2 for each project $a_i \in A$ considering all the possible priority relations according to the procedure described in Section 3.
   - Solve the single objective PBPS problem for all the priority relations identified, considering all the constraints formulated for the particular urban problem.
   - Present the best portfolios as their best options in the current context to the stakeholders and discuss them.
4. *Robustness Analysis*. In order to verify that the preference assigned to the portfolios obtained by our methodology is sufficiently stable regarding variations of the parameters of the model, an appropriate robustness analysis should be carried out in a procedure consisting of the following steps: [64,65].
   - Perturb some of the parameters used for the ranking or the sorting method (e.g. weights for the criteria);
   - Explore the possibility of relaxing or strengthening some of the imposed constraints;
   - Discuss the results with the stakeholders and conclude the analysis by identifying the preferred portfolio;
   - Considering the possibility of introducing stochastic aspects in the model, such as the probability of different scenarios happening.

We would like to stress that stakeholders can be involved at different levels in each of these steps, making our methodology strongly participatory.

3.4. When to use the PBPS methodology

Let us note that our methodology assumes that the projects a_i are independent in the sense that they are defined since the beginning, and there is no possibility of modifying them. In other words, we suppose that the robustness of strict preference implies that portfolios of lower-priority projects cannot be combined with projects of the same or lower priority to reach the performance level of the higher priority ones. We are aware that this is a limitation of our approach. However, portfolio selection procedures defined in lexicographic priorities are frequently adopted, as explained in the literature review section. Our methodology aims to formalize such a practical approach and should be adopted in situations where a lexicographic approach is retained applicable. Nevertheless, the main theoretical contribution of PBPS is that it permits combining project portfolio selection methods with noncompensatory multicriteria aggregation supplied by well-known and widely appreciated MCDA methods. PBPS is specifically relevant in at least two cases,

- when the domain related to the portfolio selection problem presents specific aspects for which it is difficult to give a quantitative numerical evaluation, as it is the case, for example, of environmental sustainability [66] or cultural heritage, which is the object of the application we present in this paper: indeed, in these cases, it is more convenient to use an outranking method which is more suitable to handle ordinal qualitative evaluations;
- when the decision maker has already experimented with an outranking method appreciating the good properties of its outputs because, in this case, the use of the same outranking method increases the confidence placed by the decision maker in the portfolio selection facilitating the decision-aiding procedure and improving the quality of the provided recommendation.

Let us also note that eventually, DMs may want to model some interactions among projects as described by [23]. Indeed, the possible interaction between projects $a_i, a_j \in A$ for which there can be an interaction in case they should be selected together can be modelled through dummy variables x_{ij} such that $x_{ij} = 1$ if both a_i and a_j are activated and $x_{ij} = 0$ otherwise. Of course, more complex interactions related to the simultaneous presence of projects from $I \subseteq A$ can be modelled using dummy variable x_I for which $x_I = 1$ if all the projects from I are selected and $x_I = 0$ otherwise.

Let us highlight that when adopting outranking methods, as in the proposed case study, we intend to use the assumption that the set of priority levels is defined to represent how the projects assigned to each priority level should further be processed [67]. We recognize that rank reversals [68] could happen in the definition of priority levels, i.e., projects assigned by the outranking model to a lower priority level are preferred over projects with a higher priority class. Nevertheless, as suggested in [69] particular attention should be devoted to those projects whose assignment is more likely to be borderline and incorrect. Thus, identifying such projects may help, also thanks to specific indicators that may be developed to understand the likelihood of pairs of projects being subjected to rank reversal situations.

Moreover, using an optimization model allows us to be very flexible and adaptable, with the ability to include different requirements related to an urban policy as constraints in our model.

Let us stress that our methodology could be applied in any real-life context, especially in the processes related to project portfolio management (PPM) [6]. PBPS can represent a very effective tool for PPM problems intrinsically based on prioritization and selecting projects.

4. The urban planning problem: cultural heritage preservation in the city of Naples

Being a World UNESCO site, the government of the city of Naples approved a management plan for its historical centre which defines the vision, the general objectives and the approach to preserve the universal values associated with its cultural heritage [see20]. This plan highlights the stakeholders involved and the strategic challenges, listing possible improvements in the area concerning tangible and intangible cultural heritage. Although the plan indicates a set of projects to be implemented, and their associated benefits and disadvantages, it fails to indicate which projects should be prioritized and which are the most beneficial for addressing the strategic challenges previously mentioned.

Moreover, in the last few years, the historic centre has become a top-rated touristic attraction, causing changes in habits and everyday life. Nowadays, the city's government has to manage a very complex regeneration process of its historic centre. Although, on the one hand, it must regenerate the most ancient part of the city, on the other hand, it must also preserve its immaterial values related to the intangible cultural heritage, which seems even more at risk.

Unfortunately, when there is an increasing need for the rationalization of expenses and resources, it is not realistic to think that all the projects will be funded, or at least they cannot be funded altogether. Therefore, the opportunity arises to select only a set of projects according to their priorities.

In the following, we describe the characteristics of our urban planning problem.

4.1. Stakeholders and criteria

Several stakeholders, such as institutional bodies, social and cultural organizations, and local businesses, were involved in the definition of the management plan [see20] which explicates their interests in four significant points of view: (1) conservation of the tangible cultural heritage; (2) promotion of the traditional craftsmanship, tourism, and local businesses; (3) improvement of the urban environment quality; and (4) social benefits for the community. These points of view, along with their respective operational criteria and subcriteria were listed in the management plan and are presented next. Therefore, we have adopted them as described in the plan, while we have further specified how they have been measured.

1. Conservation of the tangible cultural heritage point of view.
   This point of view regards the care and protection of the tangible cultural heritage, particularly with the possibility of restoring old buildings to enrich and improve their current use or to adapt them to an alternative use. These aspects can be rendered operational by considering the following two criteria.
   (a) Compatibility of the project with the affected tangible cultural heritage (notation: g_1; label: CON-COMP; unit: qualitative levels; preference direction: to maximize). For each project, we evaluate the compatibility of the building with the proposed use for the building. This criterion can be modelled through a 4-level qualitative scale with the following verbal statements and respective labels: very high (VH), high (H), medium (M), low (L).
   (b) Increasing the usability of the tangible heritage (notation: g_2; label: CON-USAB; unit: percentage; preference direction: maximize). This criterion consists of considering the increased usability of the building. We adopt a percentage scale to consider the fact that beyond a certain level, a project cannot improve the usability of the tangible heritage.
2. Promoting traditional craftsmanship-tourism-business point of view.
   This point of view regards the actions that should be taken to promote the activities of traditional craftsmanship and the expansion of the production of local products, as well as tourism and the establishment of new local businesses.
   (a) Promotion of traditional craftsmanship and traditional knowledge (notation: g_3; label: PRO-CRAF; unit: qualitative levels; preference direction: to maximize). This criterion consists of the enhancement and safeguarding in the historic city centre of traditional craftsmanship and knowledge and the enrichment of local products. Let us underline that, as it has been specified in the management plan, this criterion comprises two subcriteria:
      i. Creation of new jobs and expansion of local products. It uses a 4-level qualitative scale as in criterion 1.*a*.
      ii. Dissemination of the intangible cultural heritage. Availability of activities to promote traditional knowledge. The same type of scale as in the previous subcriterion is used.

      The two subcriteria can be combined to generate the scale of the criterion defining a 16-level qualitative scale of profiles for the criterion: VH-VH(16), VH-H(15),..., H-VH(12),..., M-VH(8),..., L-VH(4),..., L-L(1).
      Initially, the numbers from 16 to 1 were only used to code the profiles, so that, e.g. 16 is not a value, but a code for VH-VH. However, the assumption that the first subcriterion is more important than the second one was adopted. Consequently, the qualitative levels were ordered lexicographically, so that one level, represents a better evaluation of another level if
      – the first subcriterion has a better evaluation, or
      – the evaluations for the first subcriterion are the same but the second subcriterion has a better evaluation.

      For example, VH-M(14) is now better than L-VH(4) because 14 has a better evaluation on the first criterion. The levels are, therefore, now all comparable among them and ordered according to their codes.
   (b) Promotion of local entrepreneurship and businesses (notation: g_4; label: PRO-BUSI; unit: qualitative levels; preference direction: maximize). New local companies created, use of a 4-level qualitative scale as in criterion 1.*a*.
   (c) Promotion of tourism (notation: g_5; label: PRO-TOUR; unit: qualitative levels; preference direction: to maximize). Flow of visits in the city. Use of a 4-level qualitative scale as in criterion 1.*a*.
3. Quality of the urban environment point of view.
   This point of view regards the urban context as essential for improving the perception of the historic urban landscape and its conservation. There is only one criterion to render operational the quality of the urban environment point of view.
   (a) Maintenance of urban spaces (notation: g_6; label: ENV-MAIN; unit: m^2; preference direction: to maximize). This criterion consists of the urban area that has been restyled.
4. Social benefits from the community point of view.
   This point of view regards the need to improve the identity of the local communities and their knowledge of their cultural heritage. This is a point of view with the utmost importance, and it is rendered operational using two different criteria, as stated below.

Table 1
List of projects.

Project	Notation	Label
Murazione Aragonese di Porta Capuana	a_1	(Mura-Capua)
Castel Capuano	a_2	(Cast-Capua)
Complesso ex-ospedale di Santa Maria della Pace	a_3	(Comp-Maria)
Complesso S. Lorenzo Maggiore	a_4	(Comp-Loren)
Complesso S. Gregorio Armeno ed ex Asilo Filangieri	a_5	(Comp-Grego)
Insula del Duomo – Area archeologica	a_6	(Area-Duomo)
Complesso di S. Lorenzo maggiore (Area archeologica)	a_7	(Area-Loren)
Teatro antico di Neapolis	a_8	(Teat-Neapo)
Chiesa SS. Cosma e Damiano	a_9	(Chie-Cosma)
Castel dell'Ovo	a_{10}	(Cast-D'Ovo)
Complesso dei Girolamini	a_{11}	(Comp-Gerol)
San Gioacchino a Pontenuovo	a_{12}	(SanG-Corvo)
Sant'Aniello a Caponapoli	a_{13}	(SanA-Capon)
Complesso Trinità' delle Monache	a_{14}	(Comp-Monac)
Mercatino S. Anna Di Palazzo	a_{15}	(Merc-Palaz)
Chiesa San Giovanni Battista delle Monache	a_{16}	(Chie-Monac)
Complesso Santa Maria della Fede	a_{17}	(Comp-Mfede)
Carminiello al Mercato	a_{18}	(Carm-Merca)
Complesso di S. Paolo Maggiore	a_{19}	(Comp-Paolo)
Villa Ebe alle rampe di Lamont Young	a_{20}	(Vill-EbeRa)

(a) Enrichment of the cultural offer (notation: g_7; label: SOC-CULT; unit: qualitative levels; preference direction: to maximize). This criterion consists of initiatives to enrich the cultural offer, aiming to increase the city's public awareness and cultural identity.

   i. New cultural proposals. Use of a 4-level qualitative scale as in criterion 1.*a*
   ii. Increasing attendance at museums and other cultural sites. Use of a 4-level qualitative scale as in criterion 1.*a*.

   The overall scale of this criterion is built as in 2.*a* adopting the first subcriterion as the most important one.

(b) Social cohesion (notation: g_8; label: SOC-COHE; unit: qualitative levels; preference direction: maximize). Use of a 4-level qualitative scale as in criterion 1.*a*.

4.2. The interventions to preserve the tangible urban cultural heritage: Projects

In this subsection, we present a list of the projects related to the tangible urban cultural heritage included in our study. More details about these projects can be seen in the plan for the city of Naples [20]. This plan also considers some of the intangible cultural heritage, which is not included in our study. In addition, we have integrated the plan with some additional projects added over time. We discussed the characteristics of the projects and their status with a representative of the municipality, who has a thorough knowledge of the ongoing projects in the historic city centre. He provided important information about the details and the peculiarities of the projects. In Table 1 we report the selected projects and their associated notation and label. In Appendix A, for the selected projects, we list the typology of the tangible cultural heritage, the state of the building, and what type of intervention has been planned.

Moreover, for each of the projects, one or more functions, intended as the planned activities, have been identified. These are classified as:

- Tourist facilities (label U_1);
- Museum and archaeological sites (label U_2);
- Accommodations for students and the elderly (label U_3);
- Leisure Activities (label U_4);
- Record Office Archives (label U_5);
- Public Services (label U_6).

Table 2
Budgets available in K€.

Budget	$B(1)$	$B(2)$	$B(3)$	$B(4)$	$B(5)$	$B(6)$	$B(7)$
	52240	45710	39180	32650	26120	19590	13060

The functions have been listed for each project in Table A.3 in Appendix A.

To evaluate the performance of the projects, we have examined them in detail (see Table A.1 in Appendix A with all the performances for each project and each criterion).

4.3. Constraints

Constraints for the problem were discussed with the representative of the municipality. Then, to have an actual perspective on the problem, the representative of the municipality was asked to describe the restrictions to be considered in this context. At the same time, the authors formulated the constraints, adopting the x_i binary variables from the knapsack problem K2 in Section 3. We have several constraints related to different aspects.

The most important constraint is related to the budget available for the implementation of the projects. Each project $a_i \in A$ is associated with a cost s_i (see Table A.2 in Appendix A for the costs of each project). Given that, at the moment, the budget allocated to these projects still needed to be uniquely defined, several scenarios with different available budgets were considered. Denoting the available budget by B, this constraint can be formulated as

$$\sum_{\{i:a_i \in A\}} s_i x_i \leqslant B. \tag{1}$$

The scenarios with the following available budgets were tested, denoted by $B(1), \ldots, B(7)$ as specified in Table 2.

In addition, the municipality representative remarked that we could have constraints related to the type of functions each building or area will have after its restoration. Furthermore, the project's location is a strategic element in the decision. On this basis, several logical constraints can be formulated.

First, there are three main roads in the historic city centre, called "decumano", highlighted in Fig. 1. These roads are the main attractions for tourists and citizens, and there is an urgent need to restore them. For this reason, the municipality's representative suggested having a minimum number of regeneration projects implemented in this part of the city. From the map, we can see that the set of projects $A_d = \{a_2, a_3, a_7, a_8, a_{11}, a_{19}\}$ are located on one of the "decumano". The representative of the municipality suggested that among those projects, a minimum number of projects, let us say Q_d, should be carried out. We formulate this as

$$\sum_{\{i:a_i \in A_d\}} x_i \geqslant Q_d. \tag{2}$$

The municipality representative supplied the desired value for $Q_d = 4$.

Second, the ancient city centre can be divided into smaller areas, called "insulae", derived from the intersection of the "decumano" with the smaller roads called "cardines" as represented in Fig. 1. In our case, the representative of the municipality suggested that f two projects are located on the same "insula", they can generate a more significant benefit than the sum of each of their separate benefits, creating a synergy. However, he could not specify by how much was the improvement. For this reason, he indicated that he is willing to consider portfolios where at least a given number, called N, of those synergies, will be implemented. To model that, we define the set of "insula" $I = \{I_1, \ldots, I_s, \ldots, I_6\}$, such that $I_s \subseteq A, s = 1, \ldots, 6$, which contains all the projects in the sth "insula" and the $0-1$ decision variables x_{ij} with $a_i \in I_s$ and $a_j \in I_s$ such that $x_{ij} = 1$ if both a_i and

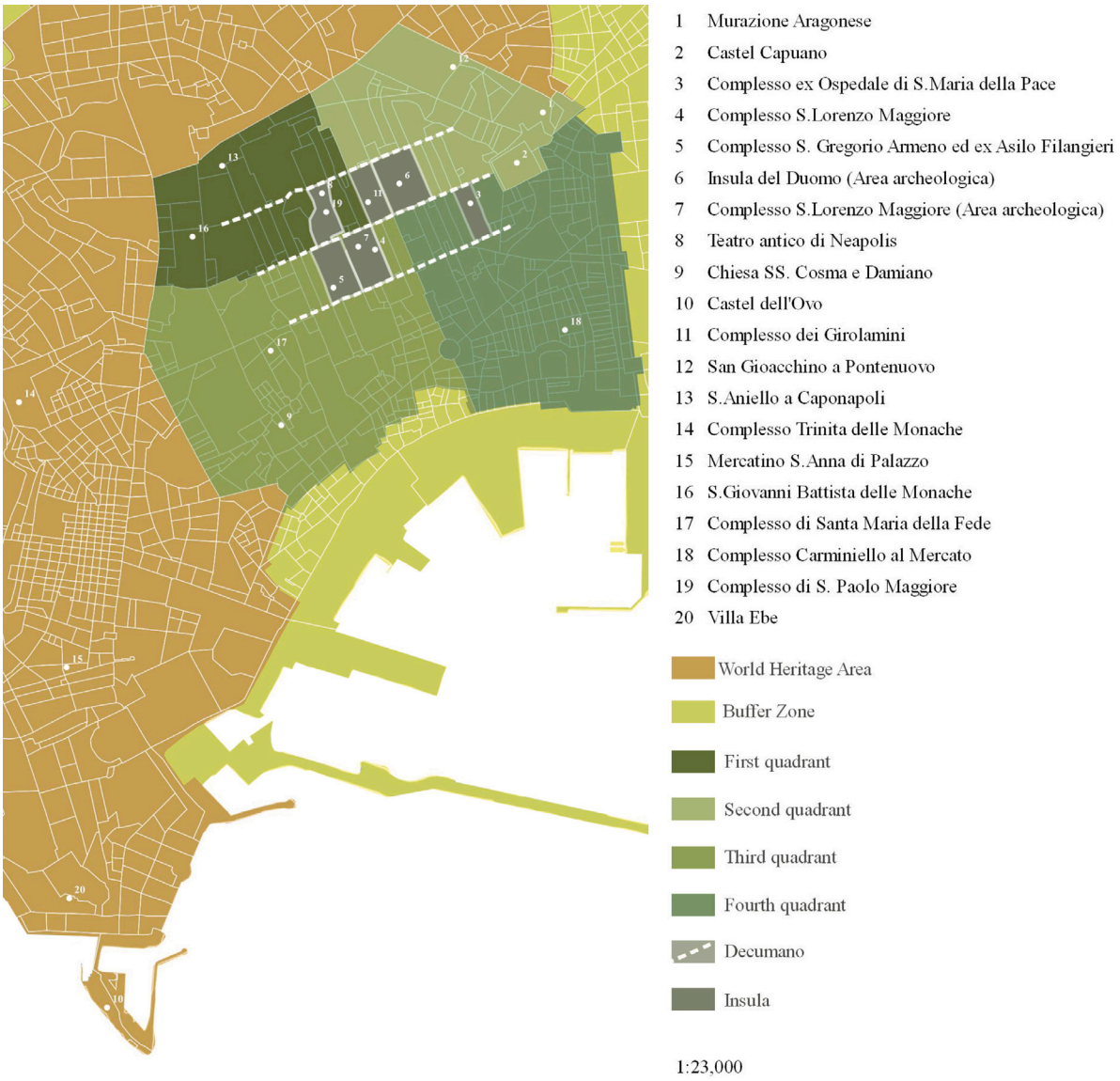


Fig. 1. "Decumano", "Insula" and Quadrants in the historic city centre.

a_j are activated and $x_{ij} = 0$ otherwise. The following set of constraints, then, should be imposed:

$$x_{ij} \geqslant x_i + x_j - 1; \tag{3}$$

$$x_i \geqslant x_{ij}; \tag{4}$$

$$x_j \geqslant x_{ij}; \tag{5}$$

$$\sum_{\{i,j:a_i \in I_s, a_j \in I_s\}} x_{ij} \geqslant N, \qquad \forall I_s \in I. \tag{6}$$

Constraints (3) to (6) specify that if two projects are located in the same "insula", then the variable x_{ij} associated with that two projects should be equal to 1. We want that at least N of the x_{ij} variables will be equal to 1, meaning we want at least N synergies. The municipality representative expressed that at least one synergy among the ones presented in every "insula" should be realized. For this reason, N was set to 1.

Third, another important aspect is the set of functions each building will have concerning the area in which it is located. For each project, we have identified all the possible functions (see Table A.3 in Appendix A). In addition, four more extensive areas called "quadrants" were considered to balance the budget distribution at territorial level. These areas of the "insula" represent four crucial areas of the ancient city centre. Note that a project can have one or more functions. In particular, if $K = \{1, \ldots, k, \ldots, 6\}$ indexes the set of the functions, and $U = \{1, \ldots, u, \ldots, 4\}$ is the set of the four quadrants, we can define the binary coefficients z_{iuk} as equal to 1 if the project a_i is in quadrant u and delivers function k, but 0 otherwise. The municipality representative indicated two types of constraints concerning these two aspects. For a specific function, a given number of projects n_k should be implemented. This constraint can be modelled as

$$\sum_{\{u \in U, a_i \in A\}} z_{iuk} x_i \geqslant n_k \qquad \forall k \in K \tag{7}$$

The representative of the municipality stressed that in what concerns the functions of the projects, he would like to have at least three projects for function U_3, i.e. accommodation for students and the elderly so that n_3 was set to 3 in constraint (7).

He also suggested that it would be ideal to distribute equally some of the functions in some quadrants. For this purpose, we define the binary

variables y_u $\forall u \in U$. The constraints are of the following type:

$$\sum_{\{i:a_i \in A:z_{iuk}=1\}} x_i \geqslant 1 - M y_u \qquad \forall k \in K, \forall u \in U \tag{8}$$

with M being a large number, and

$$\sum_u y_u \leqslant 4 - q, \qquad q \in \{0,1,2,3\}, \tag{9}$$

with q being a number between 0 and 3.

Those two constraints imply that at least one project with a given function should be open in at least $4-q$ quadrants. For example, if q is equal to 2, two quadrants should have at least one project implemented for one of the functions defined.

The municipality's representative would consider a portfolio which includes at least one project providing facilities for the citizens and one for the tourists in at least three of the four quadrants as excellent. This way, q in constraint (9) should be equal to 1.

Let us highlight that the discussion of the municipality's representative was also oriented to understand which constraints could be weakened in case of a smaller budget. The municipality representative indicated that he would happily compromise on the synergy constraints and the urban constraints related to the position of the projects to implement on the "decumano" and the "insulae".

5. Implementing the sorting method Electre Tri-nC

As highlighted in Section 3, any MCDA method could be integrated into our PBPS methodology. For this particular application, we adopted an Electre Method [for more details see70]. According to [59], our choice was led by both quantitative and qualitative criteria; in addition, the scales are rather heterogeneous, with different units: m^2, Ke, number, and verbal levels. Moreover, the choice of the scales for some criteria was somewhat arbitrary, as for example, for the criterion PRO-CRAF . Furthermore, it is not easy to define the concrete meaning of all the qualitative levels of some scales. Thus, the data are only imperfectly known, which is related to this arbitrariness when building the criteria, since there is some imprecision and/or uncertainty in this process.

Among the Electre methods we felt that the Electre Tri-nC [62] was the most adequate since the problem was already approached in the management plan as a sorting problem. In this sense, it is possible assigning each project $a_i \in A$ to an interval of contiguous classes $[C_p, C_{p'}]$, i.e. categories. The method allows to classify the projects in categories and there is a possibility of choosing any representative reference action per category. This is a much easier task in comparison to delimit the categories by (lower and upper) limiting profiles as in Electre Tri-B and nB [see71], or to define a more or less "central" reference action for each category as in Electre Tri-C [see62]. As explained in Section 3.4 we acknowledge that any Electre method can produce ranks reversals [68] in priority levels. However, we believe that the nature of the case study, the detailed information provided by the municipality's representative, and the presence of the analyst with deep knowledge of the projects allowed us to assign adequate priority levels to the reference projects. Furthermore, we believe that possible rank reversals could be uncovered and discussed thanks to the constructive interaction process.

5.1. Preference elicitation through the involvement of a group of experts

In this subsection, we present the preference elicitation process we have adopted. On the basis of [72–75], we used a focus group technique involving four experts expressing the stakeholders' points of view described in Section 4.1, that is

- an expert in conservation of the tangible cultural heritage,
- an expert in promotion of traditional craftsmanship and local products,
- an expert in quality of urban environment,
- an expert in social benefits for the community point of view.

Each expert had a deep knowledge of the local context and had experiences of urban participatory processes.

We interacted with the group of experts as follows:

1. First, for each point of view we interviewed the related expert. Every interview lasted less than one hour.
2. Second, we asked the same four experts to interact in a focus group.

The interviews were conducted by one of the authors that has a deep knowledge of the urban context in Naples. The interaction with the experts permitted modelling the preferences concerning the criteria listed, considering the different points of view.

The Simos–Roy–Figuiera (SRF) method, proposed in [76] is applied for determining the weights representing the criteria' relative importance. In the interviews and, afterwards, in the focus group, the following procedure was followed:

In the following, we shall refer to each ranking of criteria, number of blank cards and z value provided by each expert as configuration. The configurations provided by the experts in our case study are reported in Appendix B in Tables B.1–B.4.

After obtaining each of the configurations from each expert, the experts were gathered in a focus group. The focus group was smoothly implemented and lasted around 1 h. Of course, the experts had a lot of exchanges and discussions but they provided a first configuration for the criteria, reported in the Appendix B, Table B.5.

Nevertheless, after some comments and a quite long discussion, the expert also provided an additional configuration. In particular, they felt that they could change the ranking of some criteria. The weight vector $\mathbf{w} = [w_j]$ obtained by the new configuration, as well as the corresponding updated classification are reported in Table B.6 in Appendix A.

In Table 3 we report the weights originating from the individual interaction with every expert and with the focus group, in particular:

- The weight vector $\mathbf{w}^1 = [w_j^1]$ was obtained from the first configuration provided in the focus group;
- The weight vector $\mathbf{w}^2 = [w_j^2]$ was obtained from the second configuration provided in the focus group;
- The weight vector $\mathbf{w}^3 = [w_j^3]$ was obtained from the configuration provided by the expert in the conservation of the tangible cultural heritage point of view;
- The weight vector $\mathbf{w}^4 = [w_j^4]$ was obtained from the configuration provided by the expert in the promotion of traditional craftsmanship and local products;
- The weight vector $\mathbf{w}^5 = [w_j^5]$ was obtained from the configuration provided by the expert in the quality of the urban environment;
- The weight vector $\mathbf{w}^6 = [w_j^6]$ was obtained from the configuration provided by the expert in the social benefits for the community point of view.

5.2. Determining the parameters for the use of Electre Tri-NC

For the determination of the indifference and preference thresholds also called discriminating thresholds, we follow the method proposed in [77]. If there are important reasons for rejecting the hypothesis of constant thresholds, the analyst can consider using affine functions to model the discriminating thresholds. These functions can be direct (when varying with the worst performance) or inverse (when varying with the best performance). The two are equivalent, as can be seen in [77].

In what follows we present the procedure adopted for deciding the thresholds for each criterion (for the sake of the space we reported the details of the procedure in Appendix B):

Table 3
Weight vectors obtained from the focus group and the experts.

Criteria weights	g_1 CON-COMP	g_2 CON-USAB	g_3 PRO-CRAF	g_4 PRO-BUSI	g_5 PRO-TOUR	g_6 ENV-MAIN	g_7 SOC-CULT	g_8 SOC-COHE
w_j^1	20.0	8.0	14.0	8.0	2.0	17.0	14.0	17.0
w_j^2	22.7	6.4	14.5	10.5	2.3	18.6	6.4	18.6
w_j^3	13.4	18.3	6.1	18.3	6.1	18.3	13.4	6.1
w_j^4	11.3	11.3	16.1	16.1	1.6	11.3	16.1	16.1
w_j^5	4.3	14.7	11.2	11.2	11.2	21.5	7.8	18.1
w_j^6	20.8	6.3	16.6	4.2	18.7	12.5	16.7	6.1

- Criteria g_1 (CON-COMP), g_4 (PRO-BUSI), g_5 (PRO-TOUR) and g_8 (SOC-COHE): For these three criteria the scale is the same, with only four qualitative levels. There were no strong reasons to consider indifference and preference thresholds.
- Criterion g_2 (CON-USAB): The increase of the usability of the buildings is not precisely defined, leading to imperfect knowledge. The authors felt there were strong reasons favouring the need for building affine functions as explained in [77]. For the sake of the space, we reported the details of the procedure in Appendix B.
- Criteria g_3 (PRO-CRAF) and g_7 (SOC-CULT): These two criteria possess a 16-level qualitative scale. The same process as in criterion g_2 was used, but now for a discrete scale. These assumptions led to considering only constant thresholds, and the same for both criteria.
- Criterion g_6 (ENV-MAIN): Similarly to criterion g_2 the use of affine functions was adopted.

The reference actions were defined by the authors taking into account, on the one hand, the results of the focus group, and, on the other hand, the specific technical requirements of the Electre Tri-NC method (see Sections 2 and 4 in [78]). The categories of priority concerning conservation, promotion, environmental and social points of view are the following:

- Category C_1: This category contains the projects with low priority.
- Category C_2: This category contains the projects with medium priority.
- Category C_3: This category contains the projects with high priority.
- Category C_4: This category contains the projects with very high priority.

Table B.7 in Appendix B presents the set of representative actions that were constructed.

The process for assessing the veto is similar to the one used for the discriminating thresholds. Their values are presented in Table B.8 in Appendix B. Let us remark that for some criteria, no discriminating threshold was identified.

5.3. The priority relations $\gtrsim$ obtained with the Electre Tri-NC method

According to the data reported in Appendix B, we used the MCDA-ULAVAL software,[4] which implements the majority of the Electre methods, including the Electre Tri-nC method, allowing the insertion of all the data and parameters elicited.

We applied the method for each weight vector $\mathbf{w}^e, e = 1, \ldots, 6$ from Table 3 using the other necessary data of Appendix B. The results are shown in Table 4.

The projects belong to similar categories even after changing the weights. In particular, we can see that projects can be allocated to a single category or they belong to two consecutive categories. Only for some projects the use of a different set of weights leads to an assignment to different categories (a_4 and a_7) or falling between two categories (i.e., a_6, a_{13}, a_{15} and a_{16}).

6. Implementation of the PBPS model

The authors considered all the priority relations $\gtrsim$ corresponding to the different assignment supplied by the Electre Tri-nC method with respect to different weight vectors $\mathbf{w}^e, e = 1, \ldots, 6$. For our application, we adopted the knapsack problem K2 as described in Section 3 and, in particular, for case (4), given that, for all $a_i \in A$ we have that $p'(i) - p(i) \leq 2$. For each of the priority relations obtained varying the weight vectors $\mathbf{w}^e, e = 1, \ldots, 6$, the priority relation $\gtrsim$ is a complete preorder and therefore it is not necessary to find all the compatible complete preorders. In light of this, the calculation of the c_i coefficients was carried out for the classification obtained from every possible weight vector $\mathbf{w}^e$ (these are given in Table C.1 in Appendix C). The constraints included in the knapsack problem K2 are described in Section 4 and fully detailed in Appendix C. We used as value for the budget constraint (1) the budgets from Table 2 in Section 4. We denoted each possible overall configuration composed of weight vector $\mathbf{w}^e, e = 1, \ldots, 6$, and available budget $B(f), f = 1, \ldots, 7$, by $F_{\mathbf{w}^e}^{B(f)}$.

We started solving the knapsack problem K2 for each budget scenario adopting the weight vector $\mathbf{w}^1$ obtained by the configuration defined by the expert in the focus group.

At this point, the authors needed to discuss this first set of portfolios with the experts. Therefore, a second focus meeting with the same experts was run. The multiple optimal portfolios were shown to the experts gathered in the focus group. After some discussion, they were able to converge on the most preferred portfolios for the different budget scenarios, as listed in Table 5 (note that the symbol ✓means that a project should be carried out, while the symbol × denotes that the project should not be implemented).

As expected, the number or projects to be implemented decreased with a decrease in the available budget.

The experts were invited to reflect on the portfolios identified when adopting the weight vector $\mathbf{w}^1$. They provided the following comments:

- The portfolio of configuration $F_{\mathbf{w}^1}^{B(1)}$ was chosen by the experts after a long discussion. Indeed, the discussion was focused on the opportunity to implement the project a_{14} that has the highest cost. The experts underlined that it is a strategic site for the city and its historic centre. Indeed, they discussed that its reuse could generate several benefits (such as improvement of the open spaces for the citizens, improvement of the links between the upper and lower part of the city, creation of a new city attraction). However, they believed that the project a_{14} should be redefined according to the changed needs of the city and the community. Consequently, the experts agreed to compromise putting on hold project a_{14} and carrying out all the other projects.
- The portfolio of overall configuration $F_{\mathbf{w}^1}^{B(2)}$ represents a good compromise for the experts because it selects projects with different functions in different areas of the historic centre. This

[4] Available at http://cersvr1.fsa.ulaval.ca/mcda/.

Table 4
Assignment to priority categories obtained with the ELECTRE TRI-NC method varying the weights w_j.

Weight vector	$\mathbf{w}^1$	$\mathbf{w}^2$	$\mathbf{w}^3$	$\mathbf{w}^4$	$\mathbf{w}^5$	$\mathbf{w}^6$
a_1(Mura-Capua)	C_3	C_3	C_3	C_3	C_3	C_3
a_2(Cast-Capua)	C_3	C_3	C_3	C_3	C_3	C_3
a_3(Comp-Maria)	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$
a_4(Comp-Loren)	C_3	C_2	C_2	C_2	C_2	C_3
a_5(Comp-Grego)	C_3	C_3	C_3	C_3	C_3	C_3
a_6(Area-Duomo)	C_1	C_1	C_1	C_1	C_1	$[C_1, C_2]$
a_7(Area-Loren)	C_2	$[C_1, C_2]$	C_2	$[C_1, C_2]$	C_1	C_2
a_8(Teat-Neapo)	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$	$[C_3, C_4]$
a_9(Chie-Cosma)	C_2	C_2	C_2	C_2	C_2	C_2
a_{10}(Cast-D'Ovo)	C_3	C_3	C_3	C_3	C_3	C_3
a_{11}(Comp-Gerol)	C_4	C_4	C_4	C_4	C_4	C_4
a_{12}(SanG-Corvo)	C_2	C_2	C_2	C_2	C_2	C_2
a_{13}(SanA-Capon)	C_2	$[C_1, C_2]$	C_2	C_2	$[C_1, C_2]$	$[C_2, C_3]$
a_{14}(Comp-Monac)	C_3	C_3	C_3	C_3	C_3	C_3
a_{15}(Merc-Palaz)	C_2	C_2	$[C_2, C_3]$	$[C_2, C_3]$	$[C_2, C_3]$	C_2
a_{16}(Chie-Monac)	C_2	C_2	C_2	C_2	C_2	$[C_2, C_3]$
a_{17}(Comp-Mfede)	C_3	C_3	C_3	C_3	C_3	C_3
a_{18}(Carm-Merca)	C_2	C_2	C_2	C_2	C_2	C_2
a_{19}(Comp-Paolo)	C_3	C_3	C_3	C_3	C_3	C_3
a_{20}(Vill-EbeRa)	C_3	C_3	C_3	C_3	C_3	C_3

Table 5
Most preferred portfolios for the different available budgets with weight vector $\mathbf{w}^1$.

Configuration	$F^{B(1)}_{\mathbf{w}^1}$	$F^{B(2)}_{\mathbf{w}^1}$	$F^{B(3)}_{\mathbf{w}^1}$	$F^{B(4)}_{\mathbf{w}^1}$	$F^{B(5)}_{\mathbf{w}^1}$
a_1(Mura-Capua)	✓	✓	✓	✓	×
a_2(Cast-Capua)	✓	✓	×	×	×
a_3(Comp-Maria)	✓	✓	✓	✓	✓
a_4(Comp-Loren)	✓	✓	✓	✓	×
a_5(Comp-Grego)	✓	✓	✓	✓	✓
a_6(Area-Duomo)	✓	×	×	×	×
a_7(Area-Loren)	✓	×	×	✓	×
a_8(Teat-Neapo)	✓	✓	✓	✓	✓
a_9(Chie-Cosma)	✓	✓	✓	✓	×
a_{10}(Cast-D'Ovo)	✓	✓	✓	✓	×
a_{11}(Comp-Gerol)	✓	✓	✓	✓	✓
a_{12}(SanG-Corvo)	✓	✓	×	✓	×
a_{13}(SanA-Capon)	✓	×	×	×	×
a_{14}(Comp-Monac)	×	×	×	×	×
a_{15}(Merc-Palaz)	✓	✓	×	×	×
a_{16}(Chie-Monac)	✓	✓	×	✓	×
a_{17}(Comp-Mfede)	✓	✓	✓	✓	×
a_{18}(Carm-Merca)	✓	×	×	×	×
a_{19}(Comp-Paolo)	✓	✓	✓	×	✓
a_{20}(Vill-EbeRa)	✓	✓	✓	×	×

portfolio permits regenerating some marginal areas of the city suitable for citizens and not only for tourists. Indeed, preserving the identity of the historic centre and improving the quality of urban environment, are two crucial points for the experts.

- The portfolio of overall configuration $F^{B(3)}_{\mathbf{w}^1}$ was suggested as the preferred portfolio by the experts even if it is not among the optimal portfolios selected by the optimization problem K2. Indeed, the optimal portfolios were all including projects a_{12} and a_{16} instead of project a_9. However, the experts pointed out that they would have preferred a portfolio including project a_9. Let us underline that all these projects belong to the same category, i.e. they have the same priority. In addition, the sum of the costs of projects a_{12} and a_{16} is the same as the cost of project a_9.
- The portfolio of configuration $F^{B(4)}_{\mathbf{w}^1}$ was selected by the experts because it seems a good enough compromise for the available budget. Indeed, although it does not permit implementation of all the projects belonging to the category C_3, it allows regenerating of marginal areas of the ancient centre and not only the most central one, and the experts appreciated this.
- The portfolios of configuration $F^{B(5)}_{\mathbf{w}^1}$ permits to implement a very limited number of projects. However, after some discussion, the experts considered it still acceptable. Some concerns were related to the synergy constraints (3)–(6). In view of this, it was considered useful to discuss also a portfolio obtained by relaxing the synergy constraints. Comparing the two portfolios, the experts preferred that one taking into account the synergy constraints, because it contains the projects a_{19} and a_8 reckoned to be of strategic importance for the historic centre.
- The experts suggested that the budget scenario $B(6)$ and $B(7)$ were not worth investigating, given the minimal funds available and the low quality of the portfolio. We would like to stress that for budgets $B(6)$ and $B(7)$ there is no possible solution to the model that satisfies all the constraints simultaneously. Therefore, the experts were shown the portfolios obtained relaxing the set of constraints (3)–(6) related to the presence of synergies. Moreover, the number of the projects expected to be in the "decumano" was reduced to 2 and the number of student and elderly housing facilities to 1. However, for those two configurations $F^{B(6)}_{w^1_j}$ and $F^{B(7)}_{w^1_j}$ the experts could not identify a most preferred portfolio.

The second focus group meeting lasted around two hours, and the experts acknowledged that the methodology supported them in reaching a consensus around the definition of the most preferred portfolios. In general, the request to choose only one portfolio for the different budget scenarios helped focus on the city's and community's current needs. Moreover, the analysis was highly beneficial in understanding how preferences change according to the available budget.

6.1. Robustness analysis

A robustness analysis is important to verify the stability of the obtained results in case of perturbations of preference parameters, such as weights [64,79].

In the considered case study, the robustness analysis explored the results supplied by the adopted selection process in case the priority

Table 6
Stability of the project portfolio selection obtained with the weight vector $\mathbf{w}^1$, varying the weight vectors and the available budget.

Weights	w_j^2	w_j^3	w_j^4	w_j^5	w_j^6
B(1)	✓	✓	✓	✓	✓
B(2)	✓	✓	×	✓	×
B(4)	×	✓	×	×	×
B(5)	✓	×	✓	✓	×

relation is defined on the basis of the other sets of weights generated by the interaction with the single experts and the alternative set of weights identified during the first focus group (see Table 3). Therefore, with the same constraints used in the previous set of simulations, the knapsack problem K2 was solved again with the aim of finding all the multiple optimal portfolios for each budget scenario. We verified that the preferred portfolios from Table 5 could be obtained when adopting a different weight vector. In Table 6 we have reported for budget $B(1), \ldots, B(5)$ if the preferred portfolio, obtained with weight vector $\mathbf{w}^1$ and reported in Table 4, could be selected when using a different weight vector $\mathbf{w}^2, \ldots, \mathbf{w}^6$. We have excluded budgets $B(6)$ and $B(7)$ because the experts during the focus group commented that, with that amount of budget, the choice involved only very few projects, so it was considered two scenarios not worth investigating. We also excluded budget $B(3)$ because, during the focus group, the experts selected a non-optimal portfolio. In this case, we recommended that further discussion be conducted with the stakeholders to verify the selected portfolio's robustness. Let us underline that the symbol ✓in Table 5 means that the same preferred portfolio, obtained adopting the weight vector $\mathbf{w}^1$, can be selected when using a different weight vector $\mathbf{w}^e, e = 2, \ldots, 6$, in correspondence of each budget scenario. The symbol × means that the procedure does not select the same preferred portfolio for the considered weight vector and budget scenario.

The following insights can be discussed:

- Considering budget $B(1)$, the preferred portfolio (composed of all the projects apart from a_{14}) is among the multiple solutions and, consequently, can be selected for all weight vector $\mathbf{w}^1, \ldots, \mathbf{w}^6$. This means that the obtained project portfolio is quite robust and its selection, in case of budget $B(1)$, does not require further investigation.
- Portfolios generated for budget $B(2)$ and $B(5)$ are also obtained with weight vector $\mathbf{w}^2$ originated from the second configuration of the rank of criteria, blank cards and z value provided by the focus group. Similarly, the portfolio related to budget $B(2)$ can also be selected for weight vectors $\mathbf{w}^3$ and $\mathbf{w}^5$, while it cannot be selected for the weight vectors $\mathbf{w}^4$ and $\mathbf{w}^6$. Similarly, the portfolio related to budget $B(5)$ can also be selected for the weight vector $\mathbf{w}^4$ and $\mathbf{w}^5$, while it cannot be selected for weight vector $\mathbf{w}^3$ and $\mathbf{w}^6$. Then, portfolios selected for budget $B(2)$ and $B(5)$ are relatively robust, even if some further discussion with stakeholders and investigation could be beneficial.
- The portfolio related to budget $B(4)$ could be selected only with weight vector $\mathbf{w}^3$. This means that the possible selection of this portfolio needs some further discussion with stakeholders and in-depth analysis. Let us underline that the debate on this portfolio during the focus group was particularly long and difficult.

We also analysed the robustness of the obtained portfolios according to the veto thresholds. We changed the veto thresholds for up to 30% of their values for the quantitative criteria and for each of the weight vectors described above. The projects were allocated to the same categories, and the same priority relation was defined.

7. Conclusions

In this paper we presented the Priority-Based Portfolio Selection (PBPS) methodology, a new multiple criteria approach for the prioritization and the consequent selection of a portfolio of projects. The methodology is very versatile and can integrate any sorting or ranking MCDA method with a knapsack selection problem, exploiting the advantages of both approaches. PBPS can be adopted in complex contexts where, especially in case of stringent conditions in terms of investment available, projects need to be prioritized according to multiple, challenging and diverse objectives, different from the mere economic point of view. Consequently, the portfolio selection has to be based on defining a priority relation among the various feasible projects. The PBPS methodology can support local or central governments as well as non-governmental organizations in their project portfolio selection and management procedures because it permits to take into account different points of view, and it can help the final decision to have an appropriate degree of participation of the different stakeholders. From a theoretical point of view PBPS methodology gives a theoretical foundation to operational approaches already implemented in current managerial practices. Additionally, it has the merit of establishing a link with the economic theory of preference among sets of objects [7]. It fills the gap between this well-established economic theory, more speculative oriented, and the operational research methodology of the project portfolio selection, supporting real-world relevant decision problems.

We applied the PBPS methodology in a case study concerning the urban context. The proposed methodology can help manage critical concepts in the urban context, such as systems integration, flexibility, cooperative behaviour, reuse, and resource optimization. Furthermore, PBPS selects the project portfolio with an articulated decision support process that permits consideration of the projects' synergies and potential effects. In the proposed case study, we showed how PBPS worked in the challenging context of cultural heritage preservation, where huge investments are required to preserve artifacts representing the entire population's history.

Our methodology integrates the different participants' preferences and judgments into the decision process in the different steps of the procedure. In fact, in the proposed case study, the adopted decision model has been constructed with multiple interactions with a group of experts representing different points of view. The methodology results were discussed within a focus group environment involving the experts in a decision process, producing final recommendations characterized by a high level of consensus and adequately justified to the public.

The group of experts in our case study accepted the whole decision support process. In the proposed decision aiding procedure, the experts especially appreciated the contribution to attaining a general agreement considering several different criteria in such a strategic decision problem.

The positive experience of the proposed case study suggests the application of PBPS methodology in all real-world decision problems requiring a project portfolio selection based on a proper prioritization of considered projects. The adoption of PBPS is especially recommended in complex problems characterized by considering several points of view related to different stakeholders and experts. Furthermore, we believe that PBPS methodology could be improved and enhanced by some methodological developments.

Our study also presents some limitations. Indeed, the methodology, as explained in Section 3.4, can be adopted in some contexts and can be subject to rank reversals. However, as discussed in previous papers [see e.g.,68] multicriteria methods are not developed to deliver the absolute truth but to support decision makers in co-constructing a shareable solution. In addition to that, in the case study, we only studied the application of Electre Tri-nC, and we did not explore the use of any

other sorting or ranking method. However, let us point out that in other contexts, using a ranking method could also be a valid option.

In this perspective, we believe that lines for future research should include the following:

- The construction of the priority relation through different MCDA methodologies from the ELECTRE TRI-nC method used in our case study.
- The consideration of interaction effects between criteria [see80] to represent better the reality of the different applications that may be proposed.
- The study of adequate procedures to take more systematically into account robustness concerns.
- The adoption of multiobjective models [81] that can incorporate in the project portfolio selection the temporal distribution of the projects.
- The design of specific algorithms permitting handling significant project portfolio selection problems with PBPS methodology.
- The development of user-friendly software supporting the application of the methodology to the whole decision process.
- The addition of a proper robustness analysis could further strengthen our approach [82]. Further studies could deal with both uncertain project evaluations and decision maker preferences. It is also worth investigating how to evaluate synergies among project evaluations and uncertainty in portfolio constraints [83].

CRediT authorship contribution statement

M. Barbati: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing. **J.R. Figueira:** Conceptualization, Methodology, Validation, Formal analysis, Writing. **S. Greco:** Conceptualization, Methodology, Validation, Formal analysis, Funding acquisition, Writing. **A. Ishizaka:** Conceptualization, Validation, Funding acquisition. **S. Panaro:** Conceptualization, Validation, Formal analysis, Investigation, Data curation, Writing.

Data availability

Data are included in the paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.seps.2023.101595.

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