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POLITECNICO DI MILANO

Multi-Criteria Decision Aiding techniques in the sustainability arena

Monography edited by Alice Gallazzi, Simona Muratori, Claudia Romelli, Jelena Stanković

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LIST OF ABBREVIATIONS

CBA	Cost-benefit analysis
CEA	Cost-effectiveness analysis
GIS	Geographic Information Systems
IT	Information Technology
MCA	Multi-Criteria Analysis
MCDM	Multi-Criteria Decision Making
MCDA	Multi-Criteria Decision Aiding/Analysis

INTRODUCTION

People think before they act; they conceptualize before they implement. The essence of decision aiding lies in the conscious activity of deduction and modelling used to clarify a stakeholder's behaviour within a decision-making process. Within such framework, decision aiding can be defined as the "activity of the person who, using explicit but not necessarily completely formalized models, helps obtain elements of responses to the questions posed by a stakeholder in a decision process. These elements work towards clarifying the decision and usually towards recommending, or simply favouring, a behaviour that will increase the consistency between the evolution of the process and this stakeholder's objectives and value system" (Roy, 1996).

Decision aiding plays a vital role in structuring the decision-making context, fostering stakeholder collaboration, and enhancing both the transparency and legitimacy of the final decision (Figueira et al., 2005). Decision aiding science incorporates both quantitative and qualitative models, with a large spectrum of options - from the traditional models of optimisation, to statistical inference, to the techniques of artificial intelligence, to the cognitive maps as well as multi-criteria, group decision and negotiation models (Clímaco 2004).

Even when decision aiding is provided for a single decision maker, usually multiple criteria have to be taken into account. The situation is even more complex when decision aiding takes place in a multi-actor decision-making process, when a well-defined criterion is not deemed relevant or acceptable by all actors to guide the process. Therefore, Multi-Criteria Analysis (MCA) is being increasingly used to facilitate stakeholder involvement, e.g. see Bojórquez-Tapia et al. (2005), Norese (2006), Marttunen and Hämäläinen (2008), and Karjalainen et al. (2013). MCA covers all methods seeking to explicitly consider **multiple criteria** in helping individuals or groups to holistically evaluate different decision alternatives having conflicting objectives and incommensurable impacts and to explore their values in decision making (Belton & Stewart, 2002; Figueira et al., 2005).

Multi-Criteria Analysis (MCA), or Multi-Criteria Decision Analysis/Aiding (MCDA), or Multi-Criteria Decision Making (MCDM), offers a structured methodological framework to assist decision-makers in addressing such complex choices. The three terms are usually used interchangeably, although distinctions are sometimes done: for instance, MCA can be considered a broader and more exploratory concept, often applied in contexts where no immediate or formal decision is required, such as comparative assessments or preliminary analyses (Department for Communities and Local Government, 2009), while MCDA more specifically refers to a set of formalized techniques designed to support complex decision-making processes and is typically more action-oriented (Figueira et al., 2005). For the sake of clarity and consistency, the term MCDA will be used throughout this monography.

This volume aims at providing an overview of MCDA approaches for the support to decision-making in the context of sustainability. The transition to sustainable pathways requires indeed holistic perspectives integrating multiple views, sectors and actors. The volume is divided in two parts. The first part sets the theoretical background to MCDA and its development, describes the main elements of MCDA and also gives an overview of methods. The second part of the monography presents various examples of MCDA approaches applied to sustainable decision processes.

Part I

1. TOOLS FOR PUBLIC DECISION-MAKING PROCESSES

Eliot Laniado and Simona Muratori

Public intervention is necessary in decision processes involving social, environmental and land issues or other externalities because the market mechanism cannot automatically regulate such goods. The methods historically introduced to deal with these decisions are cost benefit analysis, cost effectiveness analysis and multi objectives analysis, which then developed into multi-criteria analysis. The origins and criticalities of these methods are shortly pointed out here. These methods become inadequate in a complex society where subjectivity and conflict are key elements, and participation is needed in the decision process. The methods are still useful to support the decision maker, clarify what is at stake and facilitate communication and interaction between the different actors, making the whole process transparent.

To understand why tools such as cost-benefit analysis, cost-effectiveness analysis, and multi-objective analysis were introduced, what are their limits and their role in the decision-making process, it is necessary to begin with an understanding of the reasons justifying public intervention in decisions involving social, environmental and territorial aspects or other externalities.

The **invisible hand theorem** demonstrates that if all actors in the economic system behave rationally according to the rationality of *homo oeconomicus*—i.e., maximizing their utility as consumers and their profits as producers (within the limits of their budget constraints)—and if markets adhere to the assumptions of perfect competition, the economic system will reach an **"efficient" equilibrium** through the price formation mechanism without wasting resources. The market, therefore, acts as an automatic price formation tool, which efficiently allocates the use of resources. However, there are goods for which the market not only fails to allocate use efficiently but actually leads to overexploitation. These effects are referred to as market "inefficiency" or "failure". The two main causes of market failure that specifically concern environmental goods often are linked to the violation of two principles: the principle of exclusion and the principle of individual consumption. The **principle of exclusion** holds that those who don't pay for a good are excluded from its use. However, many environmental goods—like clean air quality or scenic landscapes—are not on the market and can't be withheld from non-payers. For example, companies emit pollutants without compensating for the atmosphere's capacity to absorb them, effectively using a valuable good for free. Similarly, quarrying alters the landscape without accounting for its aesthetic or recreational value. Since these goods lack market prices, they are treated as free and thus overused. In a market system, this means that these goods are seen from the market with a price signal equal to zero, i.e., the goods are abundant, they cost nothing, and their consumption is favored over other goods. As a result, these goods are overexploited. The **principle of individual consumption** states that, for the market to function properly, the consumer appropriates a share of the production by subtracting it from the availability of others. Yet, many environmental goods can be consumed in non-rival, non-divisible way, violating this principle—one person's enjoyment of clean air or contemplation of the landscape doesn't diminish another's.

There are goods that, depending on consumption modes, can violate both principles. When they are consumed in a divisible manner (e.g., polluting air or modifying the landscape with a quarry), they bypass the market and generate no price signal. As a result, they appear to be free and become overexploited. The social cost, however, is borne by those who consume them in a non-divisible manner - breathing clean air or contemplating a scenic landscape - and, therefore, cannot act individually in the market to ensure a fair share. This asymmetry creates a disproportionate distributional effect and highlights the limits of market mechanisms. Public intervention thus becomes essential.

Within neoclassical economics, the earliest response was the development of **Cost-Benefit Analysis (CBA)**, aiming to account for these externalities by estimating the net present value of benefits and costs—including use and non-use values—to guide more efficient and equitable policy decisions (Prest & Turvey, 1965; Dasgupta et al., 1972; Boardman et al., 2018). CBA is a calculation tool applied since the 1950s in the United States to choose between alternative projects: the selected project is the one corresponding to the highest net social benefit, i.e., the one that maximizes the difference between social benefits and social costs. In CBA, all benefits and costs should be expressed in monetary terms. This implies the application of monetization methods for the estimation of social benefits and social costs, which cannot be directly derived from market prices. For example, in the case of emissions resulting from any activity, the cost related to emissions is zero for the private operator, while it corresponds to the social harm in the cost-benefit analysis. The main logical steps of a CBA are:

1. Estimation of environmental pressures based on project parameters, such as the quantity of a particular pollutant emitted.

2. Assessment of changes in environmental state as a resulting from the pressure factors exerted, e.g., the expected concentration of the pollutant in the affected area.

3. Identification and estimation of physical impacts of changes in the state of the environment, both positive and negative. This includes evaluating effects on natural ecosystems, built structures, economic activities, and human health.

4. Monetization of all identified impacts to allow for comparison across different projects or scenarios.

The main critical issues are related to the last two steps, as it can be challenging to assess all the impacts of the proposed alternatives and quantify them in monetary terms, especially when they aren't reflected in market transactions (Pearce et al., 2006; Boardman et al., 2018). Therefore, in addition to direct monetization techniques (performing all the steps of the analysis), indirect methods have been developed. Indirect monetization methods attempt to monetize directly the pressure factor or environmental state change without going through an explicit estimate of damage in physical units and their monetization (Figure 1).

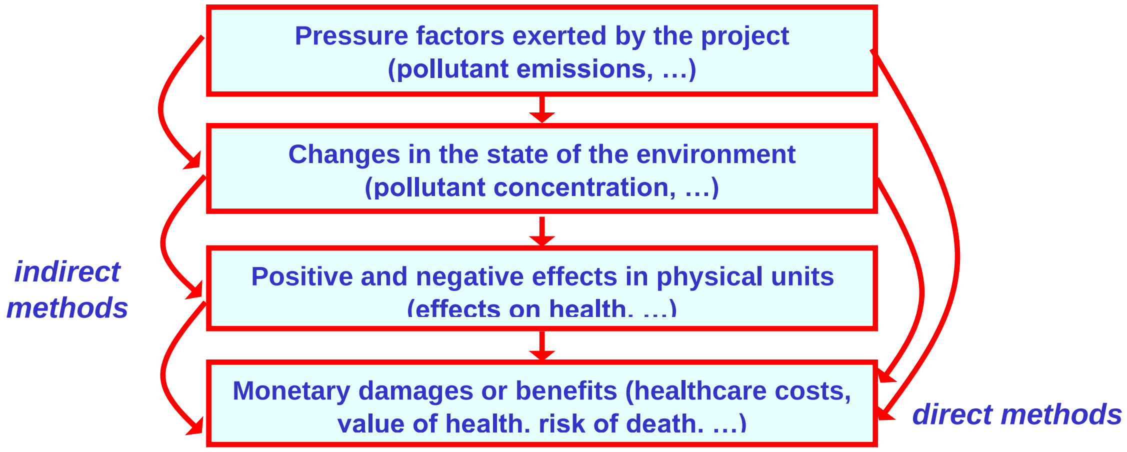

Figure 1: Direct and indirect monetization methods.

The hedonic pricing method, for example, assigns a value to the presence/absence or change in an environmental condition based on the change in real estate market prices it determines, while the contingent valuation method estimates the willingness to pay for an environmental good through interviews.

The total economic value of environmental goods and services (see Figure 2) can be differentiated in two main categories, use and non-use, thus trying to capture the full range of values assigned by people to environmental resources, beyond their presence or not on the markets (OECD, 2006). Different monetization techniques capture better different aspects of the total economic value, therefore a combination of methods should be used to identify and quantify all the relevant benefits and costs.

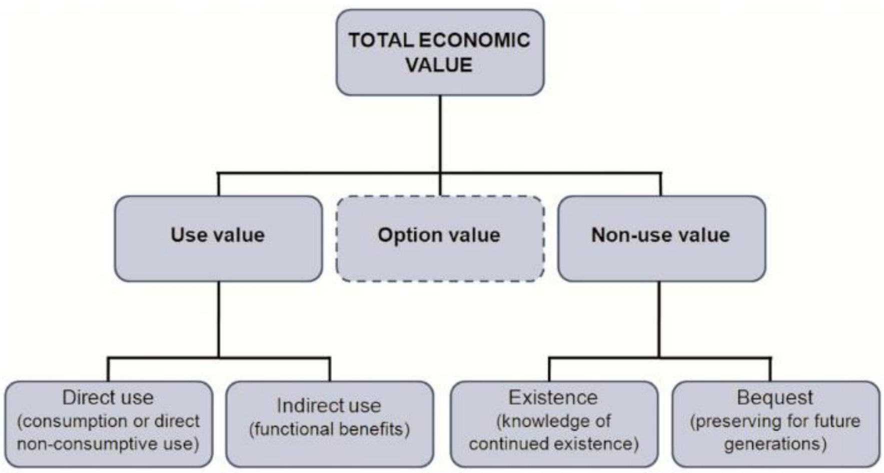

Figure 2: Total economic value framework (Grant et al., 2013).

All monetization methods, both direct and indirect, have the characteristic of reflecting existing social inequalities. For instance, the value assigned by interviewed people to their health and life depends on income: those with more resources are typically willing (and able) to pay more, leading to higher estimated values for their well-being. If decisions are based on these valuations, they tend to reproduce and increase existing disparities (Ackerman & Heinzerling, 2004; Pearce et al., 2006; Boardman et al., 2018). For example, in siting a project with potentially harmful effects, a poorer neighbourhood might be chosen over a wealthier one simply because the economic "loss" appears lower. Moreover, the choice and application of monetization methods require complex assumptions and subjective choices. These decisions can significantly influence the outcomes, reducing transparency, limiting oversight, and making meaningful public participation more difficult.

Another limitation of CBA is its inadequacy in dealing with **conflicts** implied by an alternative - both **intragenerational** conflicts, between current social groups, and **intergenerational** conflicts, between present and future generations. CBA aggregates all social benefits and costs without considering who gains and who loses, treating society as a single entity and not distinguishing between different social groups or sectors (Dasgupta et al., 1972; Boardman et al., 2018). A project may show positive overall net benefit, yet still produce serious inequalities, where one group enjoys the benefits while another bears the costs. For instance, from the point of view of CBA, a project implying a benefit of 200 for social group A and a cost of 100 for social group B (total net benefit 100) is completely equivalent to a second project implying a benefit of 50 for both social groups (total net benefit 100); but clearly the level of conflict of the two projects is likely to be quite different. This conflict often emerges too late, when the project is already being implemented, which may result in significant delays, sometimes an expensive reconversion or relocation, or even abandonment of works. CBA also tends to undervalue the interest of future generations. Intergenerational conflict is primarily linked to the use of the interest rate, which discounts future costs and benefits, making them appear less significant than immediate ones. A project that has moderate costs today in exchange for benefits of considerable magnitude but far off in time, will likely not pass a CBA, while a project that offers benefits today but leaves significant costs to future generations will be considered feasible.

The economic logic does not capture the complexity of the decision-making problem. Long-term social and environmental effects, which cannot be monetized, are often simply overlooked. Consider projects that involve the massive displacement of natural resources (e.g., water) or labour, which impoverish areas by removing their capacity to promote local development: the redistribution of income used to compensate them for the impoverishment suffered eventually turns into welfare dependency, with all its associated social damage, and it is still questioned over time.

The use of the interest rate is justified from an individual perspective because each person has a limited life horizon. This is however harder to justify from a societal standpoint, where the time horizon should span generations. Economists refer to the law of diminishing marginal utility of money: if future generations are expected to be wealthier, then a euro today is worth more than a euro in the future. However, this assumption is increasingly questioned as the depletion of natural capital and the resulting irreversible environmental damage (e.g., desertification, climate change) suggests that future generations might be poorer than the present. Some argue that a negative interest rate, i.e. giving more value to the costs and benefits of future generations, could be a promising approach (Arrow et al., 2013; Pearce et al., 2006). This debate touches on two key paradigms (Pearce & Atkinson, 1993):

- **Weak sustainability** assumes that natural capital can always be replaced by technological capital (e.g., solar energy replacing oil).
- **Strong sustainability** contends that some natural resources are **irreplaceable**, and their loss cannot be compensated by technology (e.g., biodiversity loss, climate change).

In practice, intergenerational conflict is rarely addressed, simply because future generations cannot advocate for their own interests today.

In the first half of the 1960s, **Cost-Effectiveness Analysis (CEA)** was introduced, combining the economic approach of CBA with a normative, constraint-based approach for environmental standards (Levin & McEwan, 2001; Drummond et al., 2015; Asafu-Adjaye, 2005). A typical example is urban restoration with the ultimate goal of reducing air pollution. For such projects, while different alternatives have varying costs and outcomes in terms of residual pollution, it is often neither feasible nor ethically acceptable to monetize health-related impacts. If CEA is applied, pollution is not regarded as a variable to optimize, and one or more constraints are imposed instead - such as a maximum allowable concentration of PM10 – to protect public health. Challenges and limitations of

CEA include the **responsibility of setting constraints** and the choice of the **type of constraints** (Levin & McEwan, 2001). Establishing meaningful environmental thresholds in fact would require the same complex data as monetization, such as knowing dose-response exact data. Generally, "techno-scientific-political" commissions are established, relying on epidemiological studies, when available, expert opinions, as well as on the costs that the economic system must bear to comply with the constraints. Yet, the resulting standards are often controversial, and the credibility of the process is frequently questioned. As regards the type of constraints to be chosen, constraints can be applied to pressures (like emissions from individual sources) or directly to environmental state variables (such as air quality). Pressure-based constraints (e.g., setting emissions caps for each source) may not ensure overall environmental goals are met. If total activity increases, even strict individual compliance might not prevent environmental degradation. Uniform constraints may also lead to inefficiency, since they don't account for differences in abatement costs. Ideally, those who can reduce pollution in a cheaper way should do more. State-based constraints (e.g., limits on PM10 concentrations) focus on actual environmental outcomes but make it difficult to assign responsibilities when those limits are exceeded. In both cases, enforcement requires strong, often unpopular policies, leading to widespread non-compliance or constraints being ignored altogether.

Finally, CEA generally leads to **suboptimal solutions.** CEA treats economic variables continuously, but environmental variables as binary—either within the constraint or not. Since reducing environmental impacts is generally costly, alternatives that bring conditions close to the constraints are almost always chosen, with no incentive to further improve environmental conditions, as any additional environmental benefit is not accounted for. Decision-makers thus tend to choose solutions that just barely meet the standard, creating no incentive for better performance. In densely populated areas, this can lead to a situation where multiple environmental limits are met only marginally, resulting in overall poor environmental quality. This does not mean that constraints are unnecessary. They are crucial in trying to guarantee minimum quality thresholds. However, it is necessary to further discriminate between alternatives that, while respecting the constraints, have different environmental performances.

Finally, like CBA, cost-effectiveness analysis also fails to adequately address conflict, particularly in terms of equity and public participation (Drummond et al., 2015; Neumann et al., 2016).

Another method, introduced in the second half of the 1960s, is **Multi-Objective Analysis**, which aims to address the conflict between different objectives and social groups. Its purpose is to help decision-makers explicitly weigh trade-offs, make their decisions transparent, and make more informed and accountable choices (Keeney & Raiffa, 1976; Chankong & Haimes, 1983).

A typical application involves the evaluation of multiple project alternatives based on two or more objectives. Consider the case where cost and emissions, both to be minimized, serve as the primary criteria. The two objectives are conflicting with each other, as reducing emissions generally incurs higher costs. The alternatives—denoted here as *a, b, c,* etc.— are represented in Figure 3 ass point in the two-dimensional objective plane: the ordinate indicates cost, and the abscissa represents emissions. The first operation is to apply the "Pareto efficiency criterion." According to the Pareto criterion, one alternative is considered dominated if another exists that performs at least equally well on all objectives and strictly better on at least one. In the first phase of the analysis, alternatives dominated by others are eliminated from the decision-making process. In the example considered, the remaining alternatives are those circled in Figure 3, which constitute the set of efficient solutions, or the "Pareto frontier." These alternatives are characterized by the fact that it is impossible to move from one to another by improving one objective without necessarily worsening another. This framework renders underlying conflicts between alternatives explicit. For example, choosing *f* over *i* involves an additional cost (the difference in the ordinate) in exchange for a reduction in emissions (the difference in the abscissa). The decision-maker is thus confronted with a substantive trade-off: is the marginal environmental gain in emission reduction worth the additional expenditure? If the answer is negative, they remain with *i*; if it is positive, they move to *f*, and the question can be repeated between *f* and *e*, and possibly later between *e* and *a*. Such questions can be posed iteratively along the Pareto frontier to identify the most preferred alternative in light of subjective preferences.

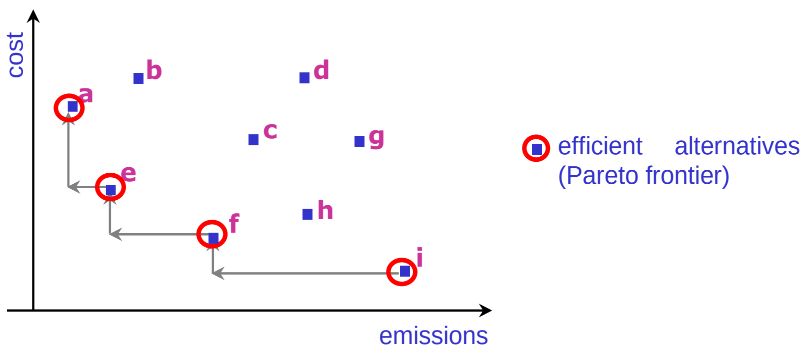

Figure 3: Pareto efficiency criterion.

In practice, decision problems rarely involve only two objectives. The objectives to consider can be numerous, some to minimize, others to maximize, such as cost, employment, greenhouse gas emissions, pollution, biodiversity, natural resource consumption, landscape protection. The complexity is further compounded in the case of linear or spatially distributed projects, where impacts vary across different territories and must be assessed regarding context-specific variables such as noise, visual intrusion, or localized pollution levels. When there are many objectives, the representation of conflicts is difficult as it often involves large matrices, which might be complex to interpret.

Building upon the foundational principles of multi-objective analysis, methods of **Multi-Criteria Decision Analysis (MCDA)** have been developed (Saaty, 1980; Roy, 1996; Belton & Stewart, 2002). These approaches seek to establish a ranking or ordering of alternatives through interaction with the decision-maker, who is, in most cases, asked to express a vector of relative weights between objectives using specific elicitation techniques. Due to uncertainty in responses, sensitivity analysis is necessary to verify the stability of the solution as the weights change. Finally, in recent years, methods have been developed not only for multi-attribute analysis but also for multiple actors, with techniques for conflict analysis and management, aiming to reach a shared solution among various stakeholders (Figueira et al., 2005).

While these methodologies are effective in supporting choice among alternatives, they assume the existence of a well-defined set of alternatives. In practice, however, the generation and formulation of alternatives often receive insufficient attention. Project proponents may lack the incentive—or the cultural orientation—to propose meaningful alternatives and may at times include contrived options solely to justify a preselected course of action. Even the default “zero alternative” (i.e., the option of non-implementation) may be rendered politically unviable due to trade-offs such as employment versus environmental protection. The search for a good solution requires generating and comparing reasonable and feasible alternatives. This requires the involvement of stakeholders beyond the project proponent, recognizing both the subjectivity inherent in evaluation and the need for conflict identification and resolution. This is the basis for the introduction of participatory procedures such as Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA), which explicitly define the roles and moments of intervention of various stakeholders, including the public (Department for Communities and Local Government, 2009; Belton & Stewart, 2002).

The evolution of tools for decision-making is consistent with the changing organizational model of society. The Fordist model - characterised by a hierarchical and pyramid-shaped structure - has gradually been joined by a network organization, where there is a plurality of actors with increasing capacity for processing and autonomy. In such a context, **governance** becomes essential as it entails the establishment of shared rules and procedures that enable self-organization and collective responsibility among participants.

This shift has several implications. Within a centralized, command-and-control paradigm, it may seem appropriate to reduce complex problems to a single objective, controlled by a single authority. By contrast, in a governance-based model, complexity must be acknowledged and addressed, given the presence of multiple actors with divergent and often conflicting goals. Participation can no longer be limited to ex post consultation aimed at legitimizing predetermined choices; rather, it must become a real, active, and proactive participation that influences the decision and helps identify critical issues and opportunities, generate alternatives, and understand and manage conflict. Moreover, information can no longer be centralized but must be shared, becoming a common knowledge base and a working tool. To reach a decision, it is no longer appropriate to propose simply a technical method, or an optimization algorithm: **Decision Support Systems (DSS)** become essential. These systems aim to generate and circulate information and to enable communication and interaction among various stakeholders, thereby fostering informed, deliberative, and accountable decision processes (Keen & Scott Morton, 1978; Power, 2002; Arnott & Pervan, 2005).

In DSS, techniques and indicators developed in the field of cost-benefit analysis, cost-effectiveness analysis, and multi-criteria analysis find a place. Monetization methods for social costs and benefits, when methodologically sound and ethically acceptable, can contribute valuable indicators. Likewise, techniques that assist in defining regulatory thresholds, standards, or preferences can enhance the quality of deliberation. However, no analytical method can or should be used to automate decision-making. The decision-making process must accommodate the roles, timelines, and subjective positions of diverse actors. In this context, evaluation techniques serve not as substitutes for judgment, but as instruments for co-producing knowledge within an inclusive, participatory process (Arnott & Pervan, 2014).

2. MULTI-CRITERIA DECISION ANALYSIS

Alessandro Luè and Simona Muratori

This chapter provides a general overview of the use of Multi-Criteria Decision Analysis (MCDA) as a support tool for addressing complex decision-making processes. To demonstrate the practical relevance and adaptability of MCDA, the case for electricity grid development discussed in the European INSPIRE-Grid—*Improved and eNhanced Stakeholders Participation In Reinforcement of Electricity Grid*— project (Poliedra, 2015; https://renewables-grid.eu/activities/inspire-grid.html) is considered throughout the chapter. Contents related to this project are based on Deliverable 4.3: Multi-stakeholder and multi-criteria methodologies.

MCDA is a structured decision-support tool designed to address complex problems characterised by multiple, often conflicting objectives, and a plurality of stakeholders with different concerns and needs. In such contexts, it is rare to find an alternative that fully satisfies all objectives or viewpoints. Instead, decision-makers must aim for a well-balanced compromise—one that accommodates competing needs and is acceptable to all involved actors. MCDA enables robust, transparent and participatory decision-making processes, promoting stakeholder engagement throughout all stages and leading to well-informed, balanced decisions.

Although hundreds of MCDA methods have been proposed, they all begin with the explicit identification of the decision-relevant objectives, typically encompassing three main dimensions: economic, social and environmental. This initial step, though seemingly straightforward, plays a crucial role in ensuring a transparent and shared decision-making framework. As outlined by Figueira et al. (2005), MCDA can reasonably contribute to:

- analysing the decision-making context by identifying stakeholders, possible actions, their consequences, key trade-offs;
- structuring and organising how the decision process unfolds;
- fostering cooperation among actors by providing tools for mutual understanding and a favourable framework for dialogue;
- elaborating recommendations based on analytical models and computational tools;
- legitimating the final decision outcome.

MCDA methods differ according to various aspects, including their theoretical foundations, the types of questions they address and the types of results they produce (Figueira et al., 2005; Hobbs & Meier, 1994). A critical review of the different methods is provided in Chapter 3.

2.1 Criteria

In MCDA, criteria reflect the preferences and value systems of stakeholders and decision-makers. They represent the potential positive and negative effects (i.e., benefits and costs) associated with each alternative. By using these criteria, MCDA helps highlight the trade-offs among competing objectives, allowing all actors to understand the strengths and weaknesses of each option. This, in turn, facilitates the identification of a compromise that reflects the collective preferences of the stakeholder group.

Evaluation criteria are typically classified into three broad categories:

- Economic costs, e.g. capital investment, operating and maintenance expenses, decommissioning costs.
- Environmental and health impacts, e.g. air pollution, biodiversity loss, landscape degradation, land use, noise, greenhouse gas emissions.
- Socio-economic aspects, e.g. impacts on local economies (agriculture, tourism, etc.) and employment, property values, and public acceptance.

The criteria can be organised hierarchically in a tree structure, which enhances transparency and comprehensibility compared to a simple list and is more likely to guarantee that all stakeholder concerns are systematically considered.

Figure 4 illustrates the developed within the INSPIRE-Grid project, used here as a case study to show the application of a standard MCDA procedure. The project focused on improving the decisional process in the planning of electricity transmission infrastructure. It adopted an MCDA-based approach to support decision-making by integrating economic, technical, environmental and social considerations from the earliest stages of the process. MCDA was chosen for its ability to ensure that the concerns of all relevant actors (among which planning authorities, Transmission System Operators, NGOs) be considered. Decision-making process on large infrastructure projects is often fragmented, with some evaluation criteria, typically those concerning environmental and social dimensions, usually introduced only in later phases. This can hinder the identification of broadly acceptable solutions and may result in delays or opposition due to dissatisfaction among stakeholders who feel their concerns were overlooked. In the context of power grid development, economic and technical benefits, such as improved supply security, system resilience, market integration and support for renewable energy, are usually well assessed. In contrast, environmental and social impacts, such as visual intrusion, land use conflicts, electromagnetic fields, and effects on biodiversity and property values, are typically addressed only during Environmental Impact Assessments (EIA). MCDA offers a formalised framework for comparing project alternatives, facilitating the identification of well-balanced solutions that reflect the diverse preferences and priorities of all stakeholders involved.

In detail, the proposed criteria tree (Figure 4) is organized into several hierarchical levels: the overall objective - in this case is represented by the grid enhancement or construction project - usually ranks at the top level of the tree, followed by macro-criteria, representing the areas impacted, which in turn are refined into other criteria up to the last level of the tree, to which indicators correspond. The elements of the tree are defined as “nodes”, which are linked by hierarchical connections. The first element of the tree is the “root”, and the final elements are the “leaves”. In the proposed tree, the “leaves” are represented by green boxes and correspond to the sub-criteria, which describe the project’s impacts to be evaluated within the MCDA. Some of these effects are related only to some life phases of the infrastructure. For instance, the effects at the local level on air pollution are mainly expected during the construction phase (e.g. due to trucks). In Figure 4, when a node is relevant only for some of the phases, the relevant phases are indicated in square brackets and denoted with C, O, D (C=construction, O=operation, D=decommissioning, all the phases if not specified). Additionally, the proposed criteria tree distinguishes between local and global impacts: the first impacts are mainly linked to the crossing of the territory by the electric lines (e.g., fragmentation of habitats, landscape damage, loss of property values); the second ones are no border dependent (e.g., GHG emissions, impacts on electricity prices or energy production). The local impacts are usually more significant for the large part of the local stakeholders (local communities, landowners, hunters, etc.), whereas the global ones could be overshadowed and not appropriately highlighted. Thus, MCDA offers the possibility to show the trade-off between the two kinds of impacts. This criteria tree was built for a generic electricity grid development project. Depending on the specific case and the stakeholders’ needs and concerns, the tree might change in shape, dimension, and specificity.

Figure 4: Generic criteria tree for assessing electricity grid development projects (Poliedra, 2015).

2.2 Indicators

Each criterion selected for a MCDA has to be associated with one or more indicators. The core of the MCDA is the identification of the evaluation criteria and the set of indicators to assess them and obtain one or more rankings of the alternatives.

Indicators are a tool to make complex phenomena measurable, with some basic functions which allow for simplification, quantification, communication, and comparability. In MCDA, indicators are used to compare the different alternatives and to order them in one or more ranked list with respect to different points of view. They are essential tools to support the decision-making process.

To be useful at the scope of the MCDA, the set of indicators must meet the following criteria:

- Possibility to attribute value. It must be possible to assess the indicators based on available data and models, preferably from established existing documentation, to ensure objectivity and ease of implementation.
- Understandability and Communicability. Indicators must be few and easy to understand, enabling both decision makers and stakeholders to familiarise themselves with their presentation and meaning.
- Completeness and non-redundancy. Indicators must be linked with the criteria in a meaningful way, but the overall indicator set must ensure non-redundancy: every impact must be described by only one indicator to prevent double counting.

Some essential properties of indicators for MCDA are listed in Table 1.

Table 1: Essential properties of indicators (Laniado et al., 2004; Smeets & Weterings, 1999).

Relevance	**Adequacy of the indicator to truly represent the phenomenon to which it refers**
Significance	Ability of the indicator to grasp the phenomenon to which it refers
Possibility to attribute value	Possibility to assess the indicator on the base of available data and models
Upgradability	Possibility to periodically repeat the calculation of the indicator with updated data
Spatial distribution	Possibility to represent the spatial distribution of the values of the indicator on the territory
Temporal distribution	Availability of time series of indicator values
Sensitiveness	Ability to measure significantly the project's effects
Response time	Ability to reflect the project's effects in a period suitable with the decisions' time
Ratio cost-effectiveness	Appropriate resources needed for the calculation of the indicator in relation to its usefulness
Communicability	Ability to communicate in a clear and understandable way the indicator's meaning to an audience of both technical and non-experts

Indicators could be either quantitative or qualitative. Quantitative indicators must be estimated through a specific calculation method, which may involve the application of a mathematical model.

The corresponding unit of measurement must always be specified. Conversely, qualitative indicators are used to describe phenomena that cannot be quantified numerically, such as landscape damage. In such cases, the indicator can be evaluated through expert judgment or stakeholder consultation, and its value is typically expressed using a symbolic scale whose meaning should be explicit, transparent and readily interpretable.

It is very important to choose the set of indicators in the most proper way and in accordance with the listed characteristics and taking into account: the territorial scale, the decisional level, the availability of data but also the costs needed for the data collection.

As an illustrative example, Table 2 presents a selection of suitable indicators associated with some of the leaves of the general criteria tree defined for the case study (Figure 4). The criteria are organized into the three main areas, corresponding to the first level of the tree: costs, environmental and health, and socio-economic aspects. Within each area, specific topics have been identified, which correspond to the leaves of the criteria tree. Each topic is assessed through one or more indicators, which must be estimated for each alternative. The "type of effect" column characterizes the nature the project's impact on each topic—such as economic, environmental or other—as well as its spatial scale (global, local, or both). For the actions New Line (NL), New Substation (NS) and Demolition (DE), the table also indicates whether the effect is positive (↑), negative (↓), uncertain (↕, i.e. the effect could be either positive or negative and requires quantification to be properly understood), or negligible/no effect (-). The last column, "Phase", highlights in grey the project phase(s) during which the impact occurs: Construction (C), Operation (O), and Decommissioning (D). The proposed indicators are intended as examples suitable for a generic electricity grid project. They can and should be adapted or modified to reflect the specific characteristics of the project and the territorial context in which it is implemented.

Table 2: A selection of the indicators proposed to assess the criteria defined for a generic electricity grid project (Poliedra, 2015).

Area	Topic	Description	Indicator	Type of effect				Phases		
					NL	NS	DE	C	O	D
COST	Investment	Investment costs include central network costs (cable costs, station costs), regional network costs	Investment costs (M€)	Economic impact	↓	↓	↓			
	Operating and maintenance	Operating and maintenance costs in a period of 30 years	Operating and maintenance costs (M€)	Economic impact	↓	↓	↓			
	Decommissioning	Decommissioning (demolition and restoration) costs at the end of the project-life	Demolition costs (M€)	Economic impact	↓	↓	↓			
ENVI	Pollutant emission	Emissions produced during the construction and demolition phases by traffic (trucks, etc.)	Pollutant (NOx, CO, PM10) emissions (µg/m3) OR	Air pollution, Local	↓	↓	↓			

			(proxy indicator) number of trucks necessary for the construction and length of the road paths							
	Valuable area for biodiversity/ habitats	Valuable areas for biodiversity or habitats affected by the project, surveyed by national or regional laws	Number of habitats crossed by the power line with a qualitative description of habitat relevance	Habitats interference, Local	↓	-	↑			
	Deforested / afforested area	Project area deforested during the construction phase and / or new areas afforested (i.e. after the plants demolition)	Deforested/afforested area	Soil consumption , Local	↓	↓	↑			
	Landscape protected areas	Areas of valuable landscape occupied or structurally/morphologically damaged by the project	Areas of valuable landscape damaged (mq)	Morphological-structural impact, Local	↓	↓	↑			
SOCIO-ECONOMIC	Loss in agriculture	The loss in farmland activities is due, not only to the soil occupation, but overall to the damage done in machining operations, irrigation, etc. There could be also damages on agricultural/farmlands products or farm animals exposed to high electromagnetic fields. Hence, the agricultural fund value could decrease.	Loss in farmland value (€/ha)	Social/economic impact, Local	↓	↓	↑			
	Tourism operators	Tourism operators in the project area, which work could be damaged by the project	Number of tourism operators in the project area and estimation of the induced economic importance of the operators	Social impact, Local	↓	-	↑			
	Transmission grid losses	The electric grid project can contribute to the reduction of electricity transmission grid losses. The expected transmission losses are calculated as the result of total disposition minus direct use on annual basis.	Electricity losses respect to the total electricity fed into the grid (MWh/y)	Economic impact, Global	↓	↓	-			
	Electricity prices	An electric grid project could contribute to the variation of the electricity prices, for example thanks to the new connections or the less amount of imported energy. However, the variation in electricity prices is due to many factors. For this reason, to calculate the expected variation of electricity prices due to the project it is necessary to use an	Variation in electricity prices (€)	Economic impact, Local	↓	↓	-			

		economic-mathematical model, which comprehends the evolution of the energy scenario.								

2.3 Data

After the construction of the criteria tree, including the identification of the set of indicators, the further step regards the collection of data needed to populate them and eventually the use of models to compute them. In fact, indicators assess the impact of the alternatives, therefore represent forecasts. Data collection and management are often rather complicated and require close collaboration with stakeholders. The availability of data highly depends on the context and has to be evaluated case by case. For instance, in large infrastructure projects such as those examined within the INSPIRE-Grid project, most of the relevant data are or should be included in the project documents (e.g. technical and economic data) and in the Environmental Impact Assessment (EIA) report and linked documentation. Some data may be available in the databases of government authorities responsible for the environment, territory or energy development (e.g. ministry of environment, ministry of cultural heritage, environmental or energy regional departments, local authorities). Other data could be collected through a specific detection through inspections. In this case, if the data collection is not feasible, since too expensive or time requiring, simpler data could be used to populate a *proxy* indicator, which is still able to describe the impact. In other cases, it may necessary to collect the indicator through interviews with experts or certain categories of stakeholders: for example, the heritage of the community, not so important from an historical or cultural point of view, but important from an emotional and affective standpoint, could be overshadowed in the EIA; this indicator requires a direct consultation of citizens through questionnaire or interviews. Finally, for all projects of a vast territorial extension, e.g. power grids' infrastructure, geo-referenced data play a key role. In such contexts, Geographical Information System (GIS) technology is an essential tool of management, analysis, mapping and visualization of geospatial data. In fact, all the greatest global challenges of our time—such as climate change, natural disasters, sustainability, and social inequity—are inherently spatial and require a geographic approach. GIS capabilities may be used to solve such complex problems. Particularly significant is the mutual enrichment that can arise from the integration of GIS and MCDA: while the former enables the analysis of large volumes of data needed for decision-making, the latter offers methodological procedures capable of processing and modelling both geographic information and decision-makers' preferences in one-dimensional values. MCDA typically employs aggregation methods, such as the average or the sum of the impacts of each alternative across an entire complex territorial system, homogenizing it. In contrast, GIS makes the spatial dimension of the analysis explicit, as it requires both the representation of the indicators used in criteria evaluation and the geographic localization of the alternatives to which those indicators refer. Such geographic data must be grounded, whenever possible, in solid scientific evidence, otherwise MCDA may result incomplete or lack credibility, potentially leading to outputs that fail to adequately reflect all the stakeholder needs.

2.4 Aggregation techniques and weights

Criteria may contribute unequally to the achievement of the overall objective and thus may be assigned different weights. The process of weighting implies making explicit the levels of trade-offs among criteria. The notion of weight assumes slightly different meanings, and carries distinct implications, depending on the specific MCDA method employed. When using MCDA methods based on weighted linear aggregation of criteria, weights do not have an absolute or intrinsic meaning; rather, they must be elicited with reference to the actual range of variation of the criteria within the specific decision context.

Various techniques have been developed for assigning numerical weights to criteria. Once weights are determined, the overall performance of each alternative can be computed, ultimately producing a ranking of the options under consideration. Weight elicitation methods help in the identification of the most appropriate set of weights—those that best reflect the perceptions and preferences of all involved actors. For this reason, active participation by stakeholders and decision-makers in the weighting phase is essential.

However, the elicitation process can be complex. Questions such as “How much more important is the cost criterion compared to the environmental criterion?” are meaningless unless framed within the context of specific ranges of variation. Indeed, the reasonableness of any response depends on the initial conditions and on the variation range of the criteria. For example, a criterion ranging from “strongly critical” to “excellent” may be more relevant, within a given decision problem, than one whose range spans only from “good” to “very good”. Naturally, different stakeholders will assign different weights to the criteria, reflecting their values and priorities. Nonetheless, reaching a consensus on weights is often more feasible than directly agreeing on preferred alternatives—particularly when stakeholders have already formed strong opinions. For instance, even the most radical environmentalist may concede that security of supply is a legitimate and important objective in the reinforcement of an electricity grid. Moreover, it should be emphasized that differences in weighting do not necessarily lead to different preferred alternatives. Even in the absence of full agreement, the weighting process helps clarify the rationale behind each decision, making explicit the trade-offs and ensuring that the final choice is at least transparent and justifiable, considering all the relevant issues.

2.5 MCDA and stakeholder involvement

MCDA applications are in their vast majority characterized by a significant involvement of a usually large and interdisciplinary group of stakeholders. Stakeholder involvement ensures that the decision-making process reflects a diverse range of perspectives, values, and priorities. By engaging stakeholders—including community members, experts, policymakers, and interest groups—early and throughout the MCDA process, decision-makers can gain valuable insights into the criteria that matter most to different groups. This collaborative approach helps in the identification and weighting of criteria, evaluation of alternatives, and interpretation of results, leading to more transparent, inclusive, and acceptable outcomes. Moreover, active stakeholder participation can enhance trust, reduce conflicts, and increase the legitimacy and effectiveness of the final decision.

According to Diakoulaki et al. (2005), this trend is clearly observable in the literature, although their direct participation is not always achieved. Several reasons are reported, while others are more difficult to be admitted. Among the latter, maybe the most important is that such a participatory process of sharing concerns, exchanging ideas, and accepting compromises is still not very common in the public or private sector. In addition, it is a costly and time-consuming process. Therefore, in some publications no hint is made on any form of stakeholders' participation, although some form of consultation with experts may have taken place at an earlier stage of the analysis.

In another group of publications (Barda et al., 1990; Beccali et al., 1998; Capros, Papathanassiou, & Samouilidis, 1988; Georgopoulou et al., 1997; Georgopoulou, Sarafidis, Mirasgedis, Zaimi, & Lalas, 2003; Hämäläinen & Seppäläinen, 1986; Kablan, 1997; Mavrotas, Diakoulaki, & Capros, 2003; Siskos & Hubert, 1983; Voropai & Ivanova, 2002), this involvement is reduced to an informal and thus not binding process, in a pre-decision stage in order to define the range of the alternatives to be considered and/or to identify major points of view; usually, there is either an explicit mention of this kind of involvement or an attempt to reflect the stakeholders' points of view through the elaboration of different sets of weights or different scenarios for the development of external conditions. Although, in these cases, the potential synergies of working together and interacting in the generation of ideas are lost, such informal involvement is of great value to capture the essence of the problems to be tackled.

In other cases, the participation of stakeholders appears as a crucial component of the whole decision process. We distinguish the following types of contribution:

- Stakeholders have actively participated in the elaboration of the criteria set and the assignment of weights (Hämäläinen & Karjalainen, 1992; Hobbs & Horn, 1997; Karni, Feigin, & Breiner, 1992). Their contribution starts with the identification of the fundamental objectives that should guide the decision process, extends to their breakdown into lower level attributes and ends up with retaining those criteria that are judged to be the most relevant for the problem to be tackled. In some cases, they furthermore contribute to the measurement and scaling of the defined criteria.

- In some applications, stakeholders take part in the establishment of alternatives, especially if they refer to constructed scenarios or action plans (Georgopoulou et al., 1998; Karni et al., 1992), while in others they express their opinion about the options that should not be retained for evaluation in the final set (Barda et al., 1990; Rietveld & Ouwersloot, 1992).
- In only a few applications (Georgopoulou et al., 1998; Hobbs & Horn, 1997; Karni et al., 1992), the involvement of stakeholders is extended in all major stages of the decision process. In Hobbs and Horn (1997) their participation is described in detail for all the steps in which the authors split the decision procedure. It is worth mentioning that it is exactly these publications which emphasize the significance of reaching consensus and suggest specific techniques to measure the disagreement between stakeholders and to achieve its resolution.

3. A SHORT REVIEW OF MCDA METHODS

Alice Gallazzi and Alessandro Luè

Decision-making processes frequently involve multiple, and often conflicting, criteria, such as financial, environmental, social and technical considerations. As discussed in the previous chapters, Multiple Criteria Decision Analysis/Aiding (MCDA) offers a structured methodological framework to assist decision-makers in addressing such complex decision problems.

The general steps of a MCDA process include defining the decision context (such the aims of the analysis the decision makers involved and other key stakeholders), identifying the alternatives, defining the objectives and criteria, eliciting the decision makers' preferences, and finally combining and synthesizing all these inputs to provide a comprehensive assessment of the options.

Over the years, hundreds of MCDA methods have been proposed, differing significantly in their theoretical background, the types of questions they address and the nature of the results they produce (Hobbs & Meier, 1994). Some methods were developed to face highly specific problems and are not easily applicable to different contexts. Others have a broader scope and have gained widespread recognition across various application fields (Figueira et al., 2005). Given the large number of available MCDA methods, decision makers often face the challenging task of selecting an appropriate decision support tool, and this choice is not always straightforward to justify. No method is perfect, nor can any method be universally applied to all types of decision problems. Each method has its own limitations, particularities, assumptions and perspectives (Ishizaka & Nemery, 2013). A possible useful way to classify MCDA methods is by the type of decision problem they are intended to address (also referred to as the *problem statement*). Although a wide range of decision problems can be identified, Roy (1981) proposed four fundamental types of decision:

1. *Choice problem.* The goal is to select the single best option or reduce the set of alternatives to a smaller subset of equivalent or incomparable "good" options. For example, a manager selecting the most suitable person for a particular project.
2. *Sorting problem.* Alternatives are assigned to ordered, predefined categories. The objective is to group options with similar behaviours or characteristics for descriptive, organizational or predictive purposes. For instance, employees can be classified into different categories such as "outperforming employees", "average-performing employees" and "underperforming employees".
3. *Ranking problem.* Alternatives are ordered from best to worst based on scores, pairwise comparisons, or other methods. The resulting ranking may be complete or partial if some options are incomparable. A typical example is the ranking of universities according to several criteria, such as teaching quality, research expertise and career opportunities.

4. *Description problem.* The aim is to describe alternatives and their consequences, typically as a preliminary step to understand the key characteristics of the decision problem.

Over time, ad hoc methods have been developed to solve each type of decision problem. Table 3 presents the most widely used MCDA methods proposed for each category (Ishizaka & Nemery, 2013).

Table 3: MCDA problems and methods (Ishizaka & Nemery, 2013).

Choice problems	**Ranking problems**	**Sorting problems**	**Description problems**
AHP	AHP	AHPSort	
ANP	ANP		
MAUT/UTA	MAUT/UTA	UTADIS	
MACBETH	MACBETH		
PROMETHEE	PROMETHEE	FlowSort	GAIA, FS-Gaia
ELECTRE I	ELECTRE III	ELECTRE-Tri	
TOPSIS	TOPSIS		
Goal Programming			
DEA	DEA		
Multi-methods platform that supports various MCDA methods			

From a more operational point of view, MCDA methods can instead be grouped into two main approaches based on their aggregation procedures (Figueira et al., 2005; Tsoukiàs, 2008):

1. *Approach based on the construction of a synthesizing parameter.* This approach relies on defining a single parameter (generally a mathematical function) that aggregates the performances across all evaluation criteria into an overall synthetic value for each potential alternative. Aggregation is typically performed through weighted sums, utility functions, or other additive models. Representative methods of this approach include MAVT, MAUT, AHP, and TOPSIS.
2. *Approach based on a synthesizing preference relational system.* In contrast to the first approach, here the aggregation procedure does not operate independently on each alternative. Instead, alternatives are compared pairwise, considering their performances relative to one another. This approach has led to the development of several methods, most of which are categorized as outranking methods, such as ELECTRE and PROMETHEE.

The following section describes the most widely used MCDA methods, grouped according to these two operational approaches (Figueira et al., 2005; Ishizaka & Nemery, 2013).

3.1 Approach based on a synthesizing parameter

This approach, which is the most traditional, is characterized by the definition of a synthesising parameter that, considering the performances of any potential alternative, assigns to them a well-defined position (generally represented by a numerical value) on an appropriate scale. Most often, the synthesising parameter consists of a mathematical function. This approach relies on the assumption of compensability among evaluation criteria, meaning that a poor performance on one criterion can be offset by a strong performance on another. Based on the overall scores, alternatives can be compared and ranked from best to worst, resulting in what is known as a complete ranking. This approach does not allow any incomparability among alternatives.

The major families of MCDA methods based on synthesizing functions are:

- Multi-attribute value theory
- Analytical hierarchy process
- Goal programming

Multi-attribute value theory (MAVT)

Multi-attribute value theory (MAVT) method (Keeney & Raiffa, 1976) assigns a numerical value (or score) to each alternative. $V(k)$ is a measure of the performance of alternative A_k with respect to all the considered criteria. Since alternative A_j is preferred to alternative A_k if and only if $V(j) > V(k)$, the method produces a complete ranking of the alternatives. The approach involves constructing value functions for each criterion independently and aggregating these using weighted sums.

In detail, the starting point is the construction of the evaluation matrix, i.e. a rectangular matrix representing the alternatives on the columns and the evaluation criteria on the rows (each measured by a specific indicator). The generic element $g_i(k)$ (row i, column k) represents the value of indicator i for alternative k.

	A1	A2	⋯	Ak	⋯
cr.1	$g_1(1)$	$g_1(2)$	⋯	$g_1(k)$	⋯
cr.2	$g_2(1)$	$g_2(2)$	⋯	$g_2(k)$	⋯
⋮	⋮	⋮		⋮	
cr.i	$g_i(1)$	$g_i(2)$	⋯	$g_i(k)$	⋯
⋮	⋮	⋮		⋮	

Figure 5: Structure of a generic evaluation matrix. The element $g_i(k)$ represents the value of indicator i (which measures criterion i) as regards alternative k

If the indicators respect proper independence conditions, not discussed here, then the value $V(k)$ assigned to each alternative A_k can be computed as an additive value function:

$$V(k) = \sum_{i=1}^{m} w_i \, v_i(k)$$

where $v_i(k)$ is a partial value function reflecting performance $g_i(k)$ and w_i is a weight that represents the contribution of criterion i to the overall score.

Given the evaluation matrix, a partial value function v_i is then associated to each criterion i. Such value function specifies the relationship between the values g_i of indicator i and a dimensionless measure of the corresponding satisfaction. The partial value function is normalized to some convenient scale (e.g., 0-1, where 0 stays for the minimum satisfaction and 1 for the maximum satisfaction among the considered values of the indicator).

Value functions may be characterized by any shape. A possible value function for the criterion "cost" is the piecewise linear function shown in **Error! Reference source not found.**. The maximum s atisfaction corresponds to the minimum admissible cost C_{min}, while over cost C_d, corresponding to the maximum available sum, the function assumes a zero value.

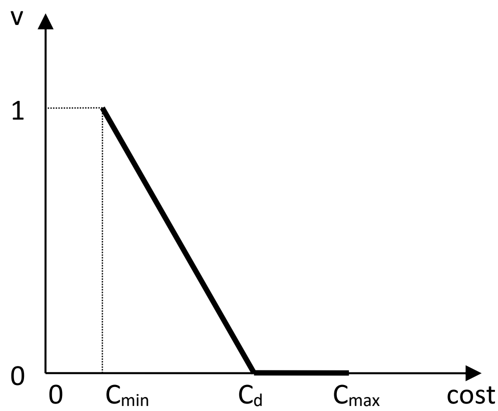

Figure 6: A generic example of value function for the cost criterion, defined in the range Cmin - Cmax

By applying value function v_i, the elements of the i-th row of the evaluation matrix are transformed in values $v_i(k) = v_i(g_i(k))$ in the 0-1 range (or in the range established for the value function). The values obtained are usually organized in a second matrix, the objectives matrix, (see Fifu), of the same dimensions of the evaluation matrix.

	A1	A2	$\cdots$	Ak	$\cdots$
cr.1	$v_1(g_1(1))$	$v_1(g_1(2))$	$\cdots$	$v_1(g_1(k))$	$\cdots$
cr.2	$v_2(g_2(1))$	$v_2(g_2(2))$	$\cdots$	$v_2(g_2(k))$	$\cdots$
$\vdots$	$\vdots$	$\vdots$		$\vdots$	
cr.i	$v_i(g_i(1))$	$v_i(g_i(2))$	$\cdots$	$v_i(g_i(k))$	$\cdots$
$\vdots$	$\vdots$	$\vdots$		$\vdots$	

Figure 7: The objectives matrix. The generic element $v_i(g_i(k))$ is contained in the 0-1 range, 1 indicating the maximum "satisfaction" and 0 the minimum one, as regards the behaviour of alternative k on criterion i

Note that criteria are considered independently from each other and that value functions give the information on the order and structure of preferences, but not on their absolute estimate. This means that the values of one row of the objectives matrix cannot be directly compared with the values of a different row. For instance, a 0 value (minimum satisfaction) for a hypothetic criterion "security of supply" could correspond to a good level of satisfaction, while for the criterion "losses variation" to a very poor level of satisfaction. This means that it is not possible to simply sum the partial performances of each alternative to obtain its overall performance, but that it is necessary to introduce coefficients of relative importance, usually called weights, for the criteria.

At this point of the analysis, before assigning weights to the criteria, it is possible to apply Pareto rule (or Pareto efficiency criterion) to discard inefficient alternatives—those that are dominated by others. An alternative is said to be dominated by another if it performs no better across all criteria and worse in at least one criterion. Formally, this means that alternative A_j is dominated by A_k if the objectives values of A_j are not larger than those of A_k for all the criteria:

$$v_i\left(g_i(j)\right) \leq v_i\left(g_i(k)\right) \qquad \forall i$$

and the value of A_j is lower than that of A_k for at least one criterion:

$$\exists h: \quad v_i\left(g_i(h)\right) < v_i\left(g_i(h)\right)$$

This dominance relationship between two alternatives can be effectively visualized through radar charts (see Figure 8). Pareto criterion cannot be applied directly to the evaluation matrix (i.e., the raw indicator values), unless all the value functions are either monotonically increasing or decreasing. Since selecting a dominated alternative would be irrational, such options can be discarded to streamline the subsequent analysis.

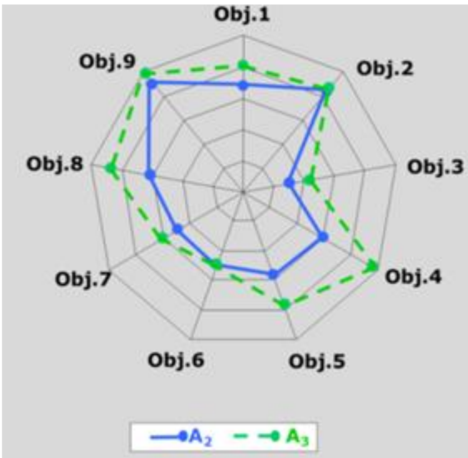

Figure 8: The radar chart comparing two hypothetical projects, A2 and A3. Objectives values are represented on axes starting from the same central point. A2 is dominated by A3 because its profile is contained by that of A3.

To complete the analysis, the weights w_i, representing the relative importance of each criterion i with respect to the others, have to be elicited. Once the weights are determined, the overall performance of alternative k, $V(k)$, can be computed as a weighted sum of its partial performances $g_i(k)$. The weights should be determined by the decision maker as they reflect his/her structure of preferences. Hence, the weight elicitation procedure can be long and complex, and requires a strong interaction between the analyst and the decision maker.

Once the overall performances $V(k)$ are calculated, the ranking of the alternatives is easily determined, ordering them from best to worst based on their scores.

The result, strongly depending on the choice of the weights and value functions, reflects the decision maker subjectivity. Potential conflicts among different actors can be measured studying different sets of weights (Luè & Colorni, 2015). A sensitivity analysis can be performed to study how the ranking varies after changing the weight values, hence how robust the ranking is.

MAVT is a very rigorous method from the formal point of view, leading to a complete ranking of the alternatives. However, it is based on the hypotheses of separability and additivity which are not easy to verify in real cases and requires a substantial interaction with decision makers to derive meaningful value functions and weights. MAVT is apt to treat well-structured problems, in a phase of the decision problem where most indicators can be assessed in quantitative terms.

A closely related theory to MAVT is the Multi-attribute utility theory (MAUT). MAUT is based upon expected utility theory, which is the systematic study of preference structures and ways to represent references quantitatively (French, 1986; Von Winterfeldt & Edwards, 1986). The advantage of MAUT is that it can explicitly incorporate uncertainty and risk preferences through utility functions. MAUT therefore facilitates complex decision contexts where uncertainty plays a crucial role. Although robust, the method demands sophisticated elicitation procedures to establish utility functions, which can be challenging in practice.

As reported by Løken (2007), the MAUT process has many benefits for the decision maker. The idea is that the process of assessing utility functions will help the decision maker to identify the most important issues, generate and evaluate alternatives, resolve judgment and preference conflicts among the decision makers and identify Siskos and Hubert (1983) were more concerned about the drawbacks of the MAUT approach. They claimed that MAUT presents many complications in the decision process, especially concerning the assessment of probabilities and attaching utilities to the criteria. To establish utility functions is a difficult and cumbersome task, because most decision makers do not have a good perception of their own risk preferences. However, MAUT is one of few MCDA methods designed especially for handling risk and uncertainties.

Analytical Hierarchy Process (AHP)

The analytical hierarchy process (AHP) was developed by Saaty (1980) and then formalized as an axiomatic theory (Saaty, 1986); see Saaty (2004) for a synthetic presentation of the method. AHP shares many similarities with Multi-Attribute Value Theory (MAVT): it assigns a numerical score to each alternative, representing its overall performance, computed as a weighted sum of the priorities assigned to the alternatives under each individual criterion. Although AHP is mathematically more complex than MAVT, it tends to simplify interactions with decision makers and is better suited to handling problems that involve qualitative judgments. Its popularity stems from its intuitive procedure and structured approach; however, it can require substantial effort when applied to larger and more complex decision problems (Ishizaka & Nemery, 2013).

The method has three main phases:

- Decomposition of the decision problem according to a hierarchy.
- Pairwise comparisons between criteria and alternatives.
- Computation of the numerical scores of the alternatives.

The decomposition phase consists in the definition of a hierarchical structure which models the problem. The top element of the hierarchy is the goal of the decision, the second level represents the criteria, and the lowest level represents the alternatives. In more complex hierarchies, more levels can be added. These additional levels represent the sub-criteria. In any case, there are a minimum of three levels in the hierarchy: goal □□criteria □□alternatives.

After structuring the problem, pairwise comparisons between elements at the same level of the hierarchy are then performed. Each level is prioritized according to its immediate upper level. This means that elements at a given level are compared with each other in terms of their contribution to an element in the upper level. For example, to prioritize the criteria at level 2 with respect to the overall decision goal, a suitable question would be: “How important is criterion i compared to criterion j in relation to the decision goal?”. Similarly, the alternatives at level 3 are evaluated with respect to each criterion in level 2. In this case, the question might be: “How preferable is alternative $A1$ to alternative $A2$ from the perspective of this specific criterion?”. The answers can be based on quantitative data about the elements, but they can simply reflect the qualitative judgment of the decision maker. Saaty predisposed a set of 9 possible qualitative answers (ranging from *Equal importance* to *Extreme importance*), and the fundamental 1-9 scale to convert the verbal evaluations to numerical values (Table 4).

The technique of pairwise comparisons is also widely used in psychology. Researchers argue that expressing a preference between only two alternatives is easier and more accurate than making judgments across all the options simultaneously (Yokoyama 1921; Thurstone 1927).

Table 4: Saaty’s fundamental scale of absolute numbers.

INTENSITY	DEFINITION	EXPLANATION
1	Equal importance	The two elements contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favour one element over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favour one element over another
6	Strong plus	
7	Very strong importance	An element is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation

The decision maker’s judgments m_{ij} are collected in pairwise comparisons matrices. For example, the matrix in Figure 9 contains the pairwise comparisons of the alternative with respect to a specific criterion. All comparisons are positive and the comparisons on the main diagonal are 1 because the alternative (or criterion) is compared with itself. AHP hypotheses that the preference or relative importance of j over i is equal to the reciprocal of the importance of i over j, i.e. $m_{ji} = 1/m_{ij}$. Therefore, these matrices are reciprocal, and their dimension is equal to the number of elements of the considered hierarchical level. The number of necessary comparisons for each comparison matrix is:

$$\frac{n^2 - n}{2}$$

where n is the number of alternatives/criteria. This formula can be explained as follows:

- n^2 is the total number of comparisons that can be written in a matrix.
- n of these represent the comparison of the alternative with itself (on the main diagonal); the evaluation is 1 and therefore not required.
- As the matrix is reciprocal, only half of the comparisons are required; the other half are automatically calculated from the first half.

Note that, even though the squared number is reduced by n and divided by 2, the number of comparisons can be very high (e.g., 10 alternatives lead to 45 questions for each criterion). Thus, the effort required to complete the matrix can be time-consuming and discouraging (Ishizaka & Nemery, 2013).

cr.1	A1	A2	A3
A1	1	m_{12}	m_{13}
A2	$1/m_{12}$	1	m_{23}
A3	$1/m_{13}$	$1/m_{23}$	1

Figure 9: An example of pairwise comparison matrix to compare three alternatives with respect to "criterion 1" (cr.1).

Once the matrix is complete, a consistency check is required to identify any contradictions among the entries, which may arise when several pairwise comparisons conflict with one another. For example, the pairwise comparisons matrix in Figure 9 is called *consistent* if, given any three elements m_{ij}, m_{ik}, m_{jk}, the equation $m_{ik} = m_{ij} \times m_{jk}$ is valid. The idea is that if alternative $A1$ is twice worthy $A2$, and $A2$ is twice worthy $A3$ (with respect to the same criterion) and there is consistency, then alternative $A1$ is four times worthy $A3$. If the decision maker's answers were consistent, all the columns of the pairwise comparisons matrix would contain the same information, and they would be proportional to each other. However, the method admits that a certain degree of inconsistency is natural, since human judgments are not always perfectly consistent. For this reason, all pairwise comparisons are carried out in a way that accounts for potential inconsistency. It can be measured using proper indices and should be kept within acceptable limits.

In practice, some level of inconsistency is almost unavoidable, especially when using Saaty's fundamental scale, which has an upper limit. For instance, if the preference of element i over j is strong ($m_{ij} = 5$) and that of j over k is moderate ($m_{jk} = 3$), then the implied preference of i over k would be $5 \times 3 = 15$, which exceeds the maximum allowed valued of 9 on Saaty's scale. Therefore,

m_{ik} can be at most 9, and this leads to inconsistency ($m_{ik} \neq m_{ij} \times m_{jk}$). To manage this, Saaty recommends that elements being compared at the same level of the hierarchy should be homogeneous, meaning that the most dominant element should not exceed the least important by more than a factor of 9. If this condition is not met, the elements should be grouped into more homogeneous subsets and evaluated separately.

Then, based on the pairwise comparison matrices, the numerical scores of both criteria and alternatives—called *priorities* in AHP— can be computed. Specifically, from each comparison matrix, a vector of priorities is obtained, showing the relative importance of the elements of a specific level of the hierarchy with respect to all the elements of the upper level. The calculation method is different depending on the matrix consistency:

- If the matrix is consistent, the vector of priorities is obtained dividing the elements in any column by the sum of its entries (i.e., normalizing it).
- If the matrix is inconsistent, and if the consistency error is sufficiently small, Saaty suggests to use the principal right eigenvector of the matrix as the best approximation of the decision maker judgments. Other methods are proposed, e.g. Barzilai, 1997.

In the simplest case of a three levels hierarchy (goal □□criteria □□alternatives), the two types of vectors are obtained:

- Local alternatives priorities. Importance of the alternatives with respect to a specific criterion.
- Criteria priorities. Importance of the criteria with respect to the overall goal.

The criteria and local alternatives priorities are then used to calculate the global alternatives priorities, which rank alternatives with respect to all criteria and consequently the overall goal. Given an alternative, the global score in the final vector corresponds to the weighted sum of its priorities with respect to the different criteria, where the weights are the elements of the criteria priorities vector.

Compared to MAVT and MAUT, AHP simplifies the task for decision makers. They are not required to directly assign performance scores to alternatives or criteria, nor to construct value or utility functions. Instead, they respond to simpler, uniform questions (pairwise comparisons) and can express their judgments in a qualitative way, using verbal assessments. As previously discussed, a drawback pf AHP is the potentially large number of questions, which can make completing the comparison matrices time-consuming and demanding for the decision maker.

Another limitation of AHP lies in the introduction of subjective elements that the decision maker cannot manage, for instance the selection of the relative importance scale when preferences are expressed qualitatively, or the definition of an acceptable inconsistency level and the method used to derive the priority vector from an inconsistent matrix.

A further limitation is represented by the dependency of the final ranking on the set of considered alternatives. Some decision theories assume that the ranking of already existing alternatives should remain unchanged when new alternatives are added, i.e. that the rank reversal phenomenon should not occur. However, AHP allows for rank reversal, meaning that the overall ranking, including the identification of the best alternative, can be influenced by the introduction of irrelevant alternatives, i.e. alternatives that are not expected to rank first. This opens the possibility of manipulating results by designing an additional alternative in such way that it affects the final ranking. Different responses to this issue have been proposed (Dyer, 1990), including the Absolute Measurement method recommended by Saaty (1987).

Goal programming (GP)

The third group of methods is commonly referred to as Goal Programming (GP). The core idea is to define an ideal goal or reference/aspiration level on each criterion and then identify the alternatives closest to these targets. These methods aim to minimize the distance—under a given definition—between an alternative and the desired goal, by interactively exploring the set of efficient solutions of a multi-objective program (Gardiner & Vanderpooten, 1997; Vanderpooten & Vincke, 1989).

A well-known example is TOPSIS, which stand for *Technique for Order of Preference by Similarity to Ideal Solution*, originally proposed by Hwang and Yoon (1981) and further developed by Lai et al. (1994). Like MAVT, the starting point of TOPSIS is – an evaluation matrix. The basic idea is to evaluate alternatives based on their geometric distance from two reference points: the ideal solution, representing the theoretical alternative with the best values of the indicator, and the anti-ideal solution, composed of the worst values (Figure 10). The best alternative is the one which has the shortest distance to the ideal solution and the furthest distance from the anti-ideal solution. More specifically, alternatives are ranked according to their *relative closeness to the ideal solution*, calculated as a ratio between their Euclidean distances from the ideal and anti-ideal alternatives. Since the indicators in the evaluation matrix are often expressed in different units, normalization is required before computing the geometric distances. In TOPSIS, normalization is done automatically, under the assumption that the satisfaction for the behaviour of the alternatives over a criterion increases (or decreases) monotonically and linearly with the value of the indicator. Weights are also assigned to the criteria before computing the distance, although the method does not prescribe a specific rule for determining these weights.

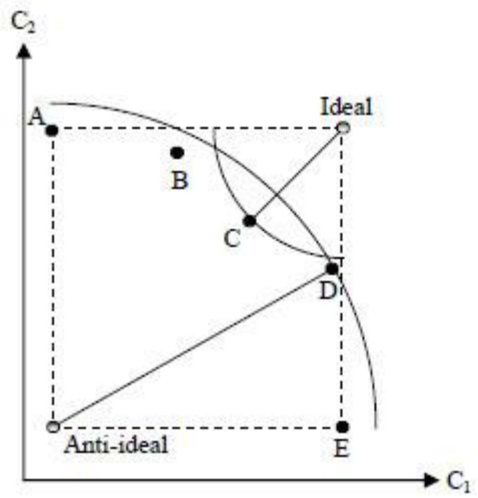

Figure 10: Representation in a two-criteria space of Ideal and Anti-ideal solutions in TOPSIS (Yilmaz & Harmancioglu, 2010).

GP techniques are often perceived as less subjective than MAVT family (Løken, 2007), and are generally more accessible to stakeholders (Ramanathan & Ganesh, 1995). They are particularly suitable for problems involving clear, quantitative objectives and goals. However, these methods have also attracted significant criticism, especially regarding the assignment of weights, the definition of aspiration levels and the normalization of the variables (Ramanathan & Ganesh, 1995). To enable the computation of geometric distances in a multi-dimensional criteria space, where each axis represents a different unit, GP methods rely on strong simplifications. These simplifications are often unrealistic and, in some cases, may lead to manipulable results, particularly by individuals who thoroughly understand the mechanism of the method.

3.2 Approach based on a synthesizing preference relational system

This approach aims at overcoming some limitations of methods based on a synthesizing function The idea is to provide deeper insight into the structure of the problem and to model the decision-makers' preferences more realistically, acknowledging possible hesitations or ambiguities in their judgments (Georgopoulou et al., 1998; Haralambopoulos & Polatidis, 2003).

The key difference lies in the multicriteria aggregation procedure, which no longer evaluates each alternative separately from the others, but instead compares pairs of alternatives sequentially. In other words, the aggregation problem is no longer approached by defining a complete preorder on the set of alternatives, but rather by constructing a synthesizing system of preference relations through pairwise comparisons. For any two alternatives, $A1$ and $A2$, the aggregation procedure aims to answer to the question: "What is the preference relation that can be validated between $A1$ and $A2$?" Possible answers include:

- $A1$ is preferred to $A2$

- $A2$ is preferred to $A1$
- $A1$ and $A2$ are equivalent
- $A1$ and $A2$ are not comparable

Within this approach, **outranking methods** are among the most widely used. Introduced by Roy (1985), the term *outranking* refers to a preference relation expressing the concept "at least as good as". Such methods are based on the following principle: when comparing two alternative, $A1$ to $A2$, across multiple criteria, $A1$ is said to outrank $A2$ if, for a weighted majority of the criteria, $A1$ performs at least as well as $A2$, and there are no strong objections from the remaining criteria (i.e., no significant "blocking minorities"). Alternatives are then compared pairwise by assigning an outranking or preference degree for each criterion. When aggregating these preference degrees across all criteria, the model determines to what extent one alternative can be considered to outrank another. Outranking methods are particularly suited for decision-making situations where full compensation between criteria is not appropriate, that is, a bad score may not be compensated for by a better score. Unlike methods based on synthesizing functions, outranking approaches allow for a partial order of the alternatives, acknowledging cases of incomparability, where two options may have different trade-offs that prevent a clear preference. These methods, often grouped under the French school of decision analysis, include the prominent families of ELECTRE and PROMETHEE methods, which will be briefly introduced in the following section. For a more detailed discussion, see Figueira et al. (2005), Figueira et al. (2013), Roy (1991, 1996).

ELECTRE

The *ELimination Et Choix Traduisant la REalité* (elimination and choice expressing reality) methods, known as **ELECTRE**, constitute one of the main branches of outranking methods. Developed as an alternative to the utility and value function-based methods, ELECTRE methods are founded on the idea that rigorous mathematical axioms are inadequate for describing complex decision-making situations, which are inherently rich in contradictions that cannot be ignored. As the acronym itself suggests, the goal of the ELECTRE methods is to remain as close as possible to the actual decision process, even if this implies preserving contradictions from a mathematical point of view.

As previously discussed, methods such as MAVT and AHP are compensatory in nature, i.e. they allow poor performance on one criterion to be offset by good performance on another. For instance, a project offering high flexibility but increasing losses might be considered equivalent to a project offering low flexibility but reducing losses. In contrast, ELECTRE methods avoid compensation between criteria and explicitly allow for *incomparability*, i.e. the possibility that no preference relationship can be established between two alternatives. In real-world cases, the compensation principle often fails to hold: it cannot always be assumed that a strong dissatisfaction regarding one criterion can be compensated by the predominance of the same alternative across the other criteria.

For example, when choosing between a small economy car and a luxury car, the price difference is so significant that the two alternatives are considered incomparable. ELECTRE methods are thus particularly suited for comparing alternatives that belong to the same category. Furthermore, ELECTRE methods explicitly acknowledge the limited discrimination ability of decision-makers. Under these assumptions, the *transitivity* property is no longer guaranteed: if project $A1$ is preferred to $A2$, and $A2$ is preferred to $A3$, it is not necessarily the case that $A1$ is preferred to $A3$.

Every ELECTRE application is based on the construction of outranking relations, which aim to comprehensively compare each pair of alternatives. An alternative $A1$ is said to outrank $A2$ when there are sufficient arguments in favour of $A1$ being at least as good as $A2$ (*concordance*), and when any arguments against it (*discordance*) are not strong enough to invalidate this judgment. The various ELECTRE methods differ in how they compute concordance and discordance indices, how they integrate these indices, and in the nature of the results they produce.

More specifically, the ELECTRE family can be classified according to the type of decision problem addressed. The first methos, ELECTRE I (Roy, 1968), and its variants ELECTRE Iv and ELECTRE Is were developed to solve choice problems, aiming at selecting, from a set of alternatives, the smallest subset containing the best options. ELECTRE II, ELECTRE III and ELECTRE IV are used for ranking problems, often resulting in a partial order of the alternatives but without assigning explicit scores. For instance, ELECTRE III generates two partial preorders of the alternatives (ascending from worst to best and descending from best to worst) that can be intersected to produce a final ranking. Lastly, ELECTRE-Tri-B (commonly referred to as ELECTRE-Tri) and ELECTRE-Tri-C are sorting methods, that assign a set of alternatives to predefined, ordered categories. The two versions differ in how the categories are defined: through limiting or boundary profiles (ELECTRE-Tri-B) or typical/central profiles (ELECTRE-Tri-C).

The ELECTRE family has been successfully applied in numerous fields, including environmental management, agriculture and forestry, energy, water management, finance, public procurement, transportation and defense (Figueira et al. 2005). The main advantage of the ELECTRE methods is their alignment with the intuitive reasoning commonly used in real-life decision-making. They explicitly recognize the limited discrimination ability of decision-makers and incorporate the possibility of incomparability. However, they also face several criticisms:

- As in AHP, the final outcome depends on the set of alternatives under consideration.
- Due the possibility of incomparability between alternatives, the resulting rankings are often partial rather than complete (see Figure 4 for an example). In particular, in ELECTRE III, the ascending and descending rankings may differ, and the different procedures of combining them into a single final ranking can introduce additional subjectivity.

- Some of the simplifications introduced to facilitate the interaction with the decision-maker are only apparent. For instance, in some ELECTRE methods, criteria weights are used but without addressing how to elicit them, or value functions are not used, but postulating the existence of monotonic evaluation matrices.
- The final results strongly depend on technical parameters, such as the weights of the criteria and discrimination thresholds, which often lack clear physical meaning and can be difficult to define precisely.

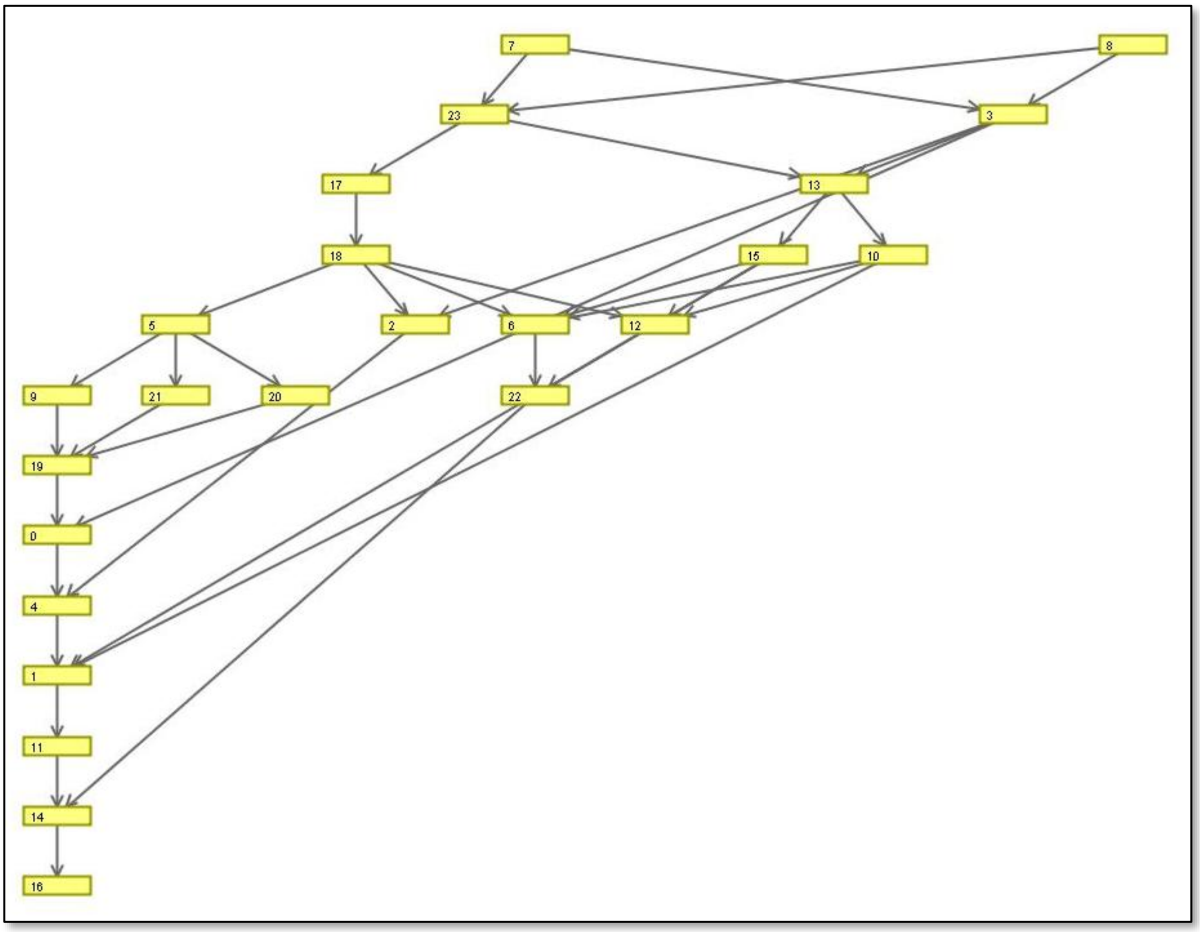

Figure 4: Example of the outcome of a ELECTRE III application (Luè & Colorni, 2009). The preference relation between 24 alternatives is shown by means of a graph. Arrows show an outranking relation between two alternatives. The rank order is not complete; for instance, alternatives 7 and 8 are incomparable.

What follows is a brief overview of how outranking relations are constructed in two key ELECTRE methods.

<u>*ELECTRE III*</u>

ELECTRE III is the most widely used ranking method within the ELECTRE family. Like all ELECTRE methods, it makes use of outranking relations. An outranking relation between two alternatives, $A1$ and $A2$, means that there are sufficient arguments to assert that $A1$ is at least as good as $A2$, and no decisive arguments against it (Roy, 1974). The method computes an outranking degree between $A1$ and $A2$ to 'measure' or 'evaluate' this assertion, based on two components: the concordance and the discordance of the statement that $A1$ outranks $A2$. The concordance represents the degree to which most criteria support the outranking assertion, based on indifference and preference thresholds provided by the decision-maker. The discordance is the degree to which one or more criteria strongly oppose the outranking, measured through veto thresholds. Therefore, both the concordance degree and discordance degree incorporate the decision maker's preference on various criteria.

ELECTRE TRI

ELECTRE TRI is a sorting (or rating) method designed to assign a set of alternatives into predefined, ordered categories, based on the philosophy of ELECTRE III. The sorting procedure evaluates each alternative according to its intrinsic merit across multiple criteria, independently of the other alternatives. A typical example is project prioritization, where projects are categorized as low, medium or high priority.

The method compares each alternative against a series of limiting profiles that define the category boundaries. Let $(C_1, \ldots, C_t)$ denote the set of ordered categories (with C_1 being the worst and C_t the best), and $(b_0, \ldots, b_t)$ of the associated profiles (such as reference projects). Each category C_i is delimited by an upper bound b_i and a lower bound b_{i-1} (see Figure 5).

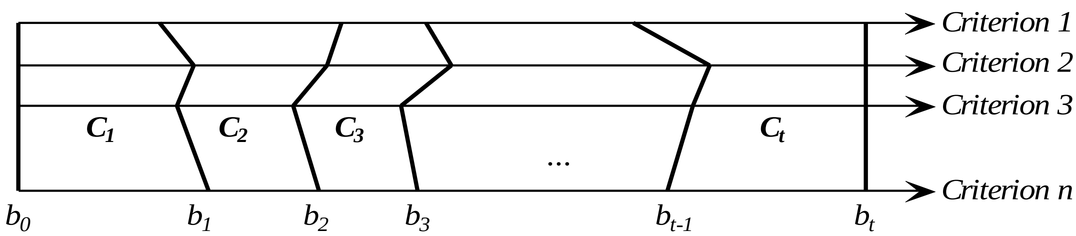

Figure 5: Representation of the profiles that separate consecutive categories (Dias & Mousseau, 2003). Each profile is characterized by a set of values as regards the considered evaluation criteria.

The outranking degrees are calculated in the same way as ELECTRE III. Using a pessimistic assignment procedure, which is the most commonly adopted approach (Dias et al., 2002), an alternative is assigned to the highest category C_i such that it outranks the lower bound b_{i-1} and is outranked by the upper bound b_i.

PROMETHEE

PROMETHEE method (*Preference Ranking Organization METHod for Enriched Evaluation*) is an alternative outranking approach to the ELECTRE family (Brans et al., 1986). This method is based on the construction of preference degrees between alternatives through pairwise comparisons. Specifically, PROMETHEE family calculates, for each pair of alternatives, a preference degree based on differences in performance over each criterion, using simple, intuitive preference functions and thresholds. From these comparisons, PROMETHEE derives positive flows (how much an alternative outranks others) and negative flows (how much it is outranked by others), leading to an overall net flow for each alternative. Two main variants exist: PROMETHEE produces a partial ranking, allowing incomparability, while PROMETHEE II leads to a complete ranking by using the net flows.

An important feature of PROMETHEE is the GAIA plane (Geometrical Analysis for Interactive Aid), a visual representation that helps decision-makers explore conflicts and trade-offs between criteria.

Compared to ELECTRE, PROMETHEE methods are simpler to understand, require fewer technical parameters, and are particularly effective for problems where decision-makers prefer direct, operational use. PROMETHEE has been widely applied in fields such as environmental management, finance, marketing, and logistics.

3.3 Comparison of the characteristics of the three main methods

Each of the MCDA methods described in the previous sections presents advantages and disadvantages (Belton & Stewart, 2002; Bouyssou et al., 2000). The construction of a value function (within the MAVT) is quite restrictive (in the sense of the conditions to be fulfilled) and requires a considerable cognitive effort on the part of the decision maker (not necessarily intuitive). On the other hand, it allows obtaining a rich result and is axiomatically well founded. The “outranking methods” are much more flexible (since there are less conditions to respect), but they risk obtaining a very poor result and are sometimes difficult to justify from an axiomatic point of view.

In order to highlight advantages and disadvantages of different methods, **Error! Reference source not found.** synthesizes the main features of the three most widely used MCDA methods (MAVT, AHP, ELECTRE) based on:

- Outcome, i.e. type of result obtained.
- Mathematical rigor.
- Rank reversal, i.e. dependence of the result from irrelevant alternatives and consequent possibility of rank reversal phenomenon, which consists of a possible inversion of the final ranking when a new (or more than one) alternative is added to (or deleted from) the initial set.

- Practicality, i.e. closeness of the method to real-world/common-sense decision-making (alignment with intuitive reasoning).
- Usability, i.e. ease or complexity of the steps which have to be undertaken from the decision maker.
- Transparency, i.e. possibility for the decision maker to understand the whole decision process, including the implications of every possible choice.
- Qualitative compatibility, i.e. ability of the method to deal also with qualitative data and therefore to be suitable in the preliminary stages of a decision-making process.

Table 5: Comparison of the main features of the three methods MAVT, AHP, ELECTRE.

	MAVT (Keeney & Raiffa, 1976)	**AHP** (Saaty, 1980, 1986)	**ELECTRE** (Roy, 1991, 1996)
Outcome	- score for each alternative - complete ranking	- score for each alternative - complete ranking	- partial rankings - specific results depending of the specific method
Mathematical rigor	- yes	- weights assigned in a non-rigorous way - arbitrariness of the choice of the qualitative scale	- arbitrariness of the assignment of thresholds and parameters
Rank reversal	- no	- dependence on irrelevant alternatives	- dependence on irrelevant alternatives
Practicality	- the theoretical aspect is prevalent	- the theoretical aspect is prevalent , but inconsistence of the decision maker is admitted	- closeness to common sense - incomparability admitted
Usability	- complex questions	- easy questions but great in number	- easy
Transparency	- possibility to understand all the steps	- arbitrariness of the choice of the qualitative scale - mathematical complexity (difficult to understand all steps)	- arbitrariness of the assignment of thresholds and parameters - mathematical complexity (difficult to understand all steps)
Qualitative compatibility	- weak: qualitative data need to be translated into quantitative ones	- excellent	- good

3.4 Conclusion

When selecting a MCDA method, several factors must be considered (Løken, 2007). Since different methods may produce different results, it is crucial to choose one that best captures the decision-maker's underlying values. Moreover, the method should be compatible with the available data and capable of providing decision-makers with all the information they require. It must also be user-friendly and easy to understand (Hobbs & Horn, 1997). If decision-makers do not understand how the methodology works, they may perceive it as a "black box", which can undermine their trust in the resulting recommendations.

In fact, selecting an MCDA method can be considered a multi-criteria problem in itself. Each method has specific strengths and limitations, and it is not possible to assert that one approach is universally superior to the others. Different decision-makers may disagree about which methods are most valid and appropriate. The choice often depends on the preferences of both the decision-maker and the analyst. It is essential to consider each method's suitability, reliability and ease of use. Importantly, the use of different methods will likely yield at least partially different recommendations. This should not be interpreted as a flaw in the methodologies themselves, but rather as a reflection of the distinct ways in which they process information and highlight different dimensions of the decision problem (Løken, 2007).

Hobbs and Horn (1997) emphasized that the choice of method can significantly influence decision outcomes. They argued that switching from one method to another can have greater impact than changing the individual applying it. For this reason, Hobbs and Meier (1994), as well as Hobbs and Horn (1997), recommended that, whenever feasible, multiple MCDA methods should be used within a single decision making process. This approach provides a more comprehensive foundation for decisions. Furthermore, decision-makers should be encouraged to reflect upon and, if necessary, revise their values in response to the initial results produced by the methods.

As Roy (1999) and Clímaco (2004) point out, the purpose of decision-aiding tools (particularly MCDA) is not to reveal hidden truths, but rather to support the construction of individual convictions, collective decisions, and compromises between multiple and often conflicting rationalities, stakes and value systems. MCDA does not aim to unify or synthesize divergent value frameworks, reasoning approaches, or legitimacy principles when they come into conflict within the same decision process. Nevertheless, in many cases, MCDA can and should facilitate structured debate, support participation and negotiation, foster a climate of trust and promote a shared understanding of the problem at hand.

Part II

1. MCDA Applications

MCDA approaches are widely applicable across a range of decision-making contexts, particularly where multiple, often conflicting, objectives must be considered. These methods are valuable in both public and private sectors, supporting complex choices in areas such as urban planning, environmental management, transportation policy, and infrastructure development.

Over the past years, there has been a significant rise in the application of MCDA methods in sustainability research (e.g. Diaz-Balteiro et al., 2017; Rui Figueira et al., 2016). In fact, MCDA seems to be an adequate tool to deal with the assessment and resolution of conflicts arising from the many perspectives – ecological, socio-economic, technological, ethical – involved in sustainable development policies (Munda, 2005). Cegan et al. (2017) found that applications related to natural resources and energy were the most common in the papers reviewed, followed by air, water and waste management.

In the following sections, a series of MCDA applications are presented to illustrate the diversity and practicality of these approaches. The chapter is organised thematically and shows a selection of contexts where MCDA might be applied by presenting collection of research abstracts. These examples were gathered during a seminar organized by Consorzio Poliedra in September 11-13, 2023, in the context of the EU-funded UR DATA—Twinning for Excellence in Smart and Resilient Urban Development: Advanced Data Analytics Approach—project. The event brought together researchers from different countries and different fields of expertise to share insights and experiences related to MCDA implementation. The scientific committee of the seminar was composed by the following scholars:

Marta Bottero (Politecnico di Torino, Italy)

Alberto Colorni (Poliedra-Politecnico di Milano, Italy)

Peter Nijkamp (Open University, Heerlen, Netherlands)

Alessandra Oppio (Politecnico di Milano, Italy)

John Östh (OsloMet, Oslo, Norway)

Jason Papathanasiou (University of Macedonia, Thessaloniki, Greece)

Pavle Petrović (Serbian Academy of Science and Arts, Serbia)

Aura Reggiani (University of Bologna, Italy)

Carlo Sessa (ISINNOVA, Rome, Italy)

Jelena J. Stanković (University of Niš, Serbia)

Alexis Tsoukias (Paris Sciences & Letters University, France)

1.1 Tools for data-driven decision support

The rise of digital technologies, data-sharing ecosystems, and advanced analytical tools have expanded the potential of MCDA, making it more accessible, adaptable, and impactful across a wide range of applications. They support MCDA by integrating diverse data sources and streamlining analytical processes within decision-making frameworks. These tools facilitate the structured application of MCDA methodologies by enabling the efficient collection, processing, and visualization of both quantitative and qualitative data, thus offering a better reflection of the real case to be evaluated (e.g. Liou et al., 2019; Tian et al. 2023). They support seamless integration of stakeholder inputs, preference modelling, criteria weighting, and alternative evaluation—all within unified platforms. Together, these developments support more informed, transparent, and reliable decision processes in fields such as urban planning, public policy, and sustainability.

The abstracts in this section reflect this growing intersection, highlighting different ways in which digital tools, analytical methods, and collaborative data practices are being used to better understand complex problems and support more effective solutions. From the implementation of MCDA in open-source programming environments, to the evaluation of urban performance using advanced efficiency models (Kourtit et al., 2023), and the development of institutional data ecosystems for sustainability, each contribution highlights how technology and data can be harnessed to support more informed, strategic, and collaborative actions across sectors and scales.

Title	**Python based implementations of Multiple Criteria Decision Aid methods: a comprehensive approach**
Author(s)	Jason Papathanasiou (University of Macedonia)
Abstract	Multiple Criteria Decision Aid (MCDA) is an applied branch of the OR discipline that continues to grow today with an increasing number of publications every year. Such methods have been successfully applied to all possible domains and many variations of these methods there have been developed during the course of the last decades. There are many software packages available for MCDA, however most of them are proprietary software that do not fall in the free and open software category and as such are not fully available to many researchers. Python on the other hand is a robust computer language that is widely used and well known for it relatively easy learning curve that suits the academic perspective. In addition,

	Python is free; it has a wide variety of libraries on all topics of scientific interest; the code is clean and easily read by the non fully familiar programmer and is expected to continue developing for many years to come. Implementing an MCDA method in a language like Python offers many advantages; it helps researchers understand each step of the various methodologies with their quirks and perks; choose the data input wisely; create a proper conceptual model and at the very end check the results and interpret them correctly.
Title	**A multidimensional profile assessment of stellar cities by means of DEA modeling**
Author(s)	Peter Nijkamp (Open University) Karima Kourtit (Open University) Soushi Suzuki (Hokkai-Gakuen University)
Abstract	Asia hosts several mega-cities with great economic power, which are often in a mutual competitive relationship. Despite smart specialisation and heterogeneity on national and global markets, they are often in pursuit of the highest possible socio-economic outcome so as to outperform their peers in this dynamic region. The present study seeks to present an operational comparative framework for judging the complex performance of several (12) large urban agglomerations in Asia. In the framework of this paper, these cities are called 'stellar cities'. Two particular research challenges are addressed: (i) the development and application of a new Data Envelopment Analysis (DEA) approach, culminating—after a cascade of sequential analytical steps—in an Autoconfiguration Target Model which serves as a quantitative statistical tool for evaluating the (relative) multidimensional goal-oriented performance of the cities concerned; and (ii) a new functional interpretation of the DEA slack space for the possible improvement of inefficiently operating cities on the basis of Amartya Sen's capability theory. In the paper, we use an extensive database on 12 Asian stellar cities, extracted from the annual Global Power City Index (GPCI) system which contains more than 60 urban performance indicators, which has been constructed by the Institute of Urban Strategies (Tokyo). We find that the performance ranking of these Asian mega-cities shows the 'winners', but also a high variability, with several positive and negative outliers. We conclude that there is clearly scope ('capability') for further improvement of the efficiency of most Asian cities in various specific policy domains, as shown by the DEA results.

Title	**E015 Data Space enabling Multi-Stakeholders Data Exchange to improve Sustainability**
Author(s)	Emiliano Sergio Verga (Cefriel) Michele Bonardi (Cefriel) Marco Rocco (Cefriel)
Abstract	Sustainability improvement needs the adoption of various digital solutions, both to promote behavioural change of citizens, and to support institutions in making decisions. All these digital solutions should be realized by public and private players, and need to be fed by real-time data, coming from other players: it is important to promote and manage many-to-many data exchange, preserving every single player data sovereignty. E015 is a multi-years institutional Data Space of Lombardy Region Government, that, according to a common legal and organizational framework, enables the publication and request for use of data flows by public and private players. E015 has enabled more than 560 data exchange relationships, and it is successfully adopted to monitor and improve sustainability; for example, environmental data exchange enabled by E015 improves dams' safety or mitigates pollution related to agriculture activities. E015 is widely adopted in mitigating natural risk: civil protection alerts data are integrated on the websites of municipalities to inform citizens, or the same data are used by institutions to monitor glaciers. Electric mobility strategic planning by Lombardy Region Government is performed with a data-driven approach, based on E015: Charge Point Operators (CPO) give access to data related to the charging infrastructure they manage, to support the Public Administration in evaluating sustainability indicators and identifying where new infrastructures need to be financed. CPOs are engaged as data providers and the clauses requesting the publishing of data within the E015 Data Space are directly added to public tenders, with no additional costs for the Public Administration in leveraging data from companies. E015 successful model has been adopted also on other scale levels: for example, it is implemented to make Malpensa Cargo supply chain more efficient, or within the DXM – Data eXchange Marketplace – of the MIND Milano Innovation District, to foster innovation and coopetition between tenants.

1.2 Spatial planning of urban and rural landscapes

In both urban and rural landscapes, planning decisions must balance environmental, social, economic, and technical factors—ranging from land use allocation and infrastructure development to conservation and resource management. MCDA provides a transparent and systematic framework to assess these competing interests, enabling planners to consider diverse stakeholder perspectives and long-term impacts. MCDA can incorporate both quantitative and qualitative data, account for diverse stakeholder values, and be adapted to suit a wide range of planning scales and thematic areas. It is particularly useful in contexts where decisions have long-term spatial implications—such as land-use planning, infrastructure development, resource management, landscape conservation, and regional policy design. Therefore, its application in spatial planning promotes more informed, equitable, and sustainable decisions, particularly when integrated with GIS and other spatial data technologies (Carver, 1991)

The contributions presented in this section reflect the growing adoption of MCDA in addressing diverse challenges across both urban and rural environments. Research topics include assessing accessibility of neighbourhoods and promoting sustainable mobility, evaluating ecosystem services with the AHP process (Rovai et al., 2023), managing cultural landscapes, or identifying strategic development areas. These studies illustrate how MCDA can serve as a powerful decision-support framework to guide spatial strategies toward more balanced, sustainable, and inclusive outcomes. Masi et al. 2024 namely found that community integration for the definition of MCDA criteria and weights for a project location enhances the social acceptability of engineering measures and thus their long-term adaptability to the environment and the community.

Title	**Accessibility Indices as a Decision Support Tool in Land-use Planning**
Author(s)	Eirik Melå Skjelsvik (Norwegian University of Science and Technology)
Abstract	A central idea in the literature on urban form and travel behavior is that urban land-use characteristics, such as the distribution, density and distance between housing and urban opportunities, influences peoples travel behavior. By extension, residential areas with different accessibility profiles will have varying potential for sustainable travel behavior. The concept of accessibility provides a unifying concept for analyzing and communicating the interlinkages between land-use characteristics and transport. At the same time as the concept has gained widespread interest among academics, it is still a significant gap in applying accessibility as a tool that can guide policymakers in land-use planning practice. The goal of this paper is to develop an accessibility-based decision-support method that can be used in spatial planning to prioritize areas for residential development that has a high potential for environmentally friendly-travel behavior. By utilizing highly detailed population data and a geocoded version of the Norwegian Business Entity registry at the address level, the paper develops and tests the accessibility-based decision support method in two Norwegian urban regions with different urban structures. The two regions are

	the monocentric Trondheim region and the polycentric region of Stavanger-Sandnes. The method developed in the paper builds on repeated cumulative accessibility measurements with walking, bicycling and public transport to the most important destinations in the Norwegian Travel Habit Survey with a cut-off value of 10, 20 and 30 minutes for walking, bicycling and public transport respectively. Based on the proportion of trips to the different destinations and depending on the characteristics of the activities, notably if it is the number of activities that matters from a travel behavior perspective or if it is the distance to the closest service that matters, the paper develops a system for weighting accessibility to different types of destinations into integrated mode-specific maps for walking, bicycling and public transport accessibility. Next, the paper combines the weighted mode-specific maps in two composite indices, one for local accessibility to activities and one for regional accessibility to activities. The two indices are finally combined into a final normative decision-support map for residential developments for the two urban regions that can be used by policymakers to guide new residential developments to highly accessibility areas with a potential for environmentally friendly travel behavior.
Title	**MCDM to assess municipalities' inclination to heritage-based development processes in inner areas**
Author(s)	Marco Rossitti (Politecnico di Milano) Francesca Torrieri (Politecnico di Milano)
Abstract	The Covid-19 pandemic has forced reflection on the leading urbanization model's limits and placed greater attention on marginal areas' role. In Italy, the related scientific and media debate has focused on the territorial dimension of inner areas. Since 2014, these territorial realities have represented the target of an innovative national cohesion policy to tackle depopulation and the ongoing shrinking dynamics: the National Strategy for Inner Areas (SNAI). Indeed, Italian inner areas are endowed with extraordinary natural capital and are based on settlement models far from urban density. Thus, they seem to respond perfectly to the newly raised living needs. However, leaving aside the optimistic rhetoric, strong political and administrative choices are necessary to trigger a 'return process' based on this wider attention towards inner areas, thus countering humankind's natural tendency to concentrate in urban realities. In this light, the contribution proposes a tool, based on MCDM, to support decision-makers in the SNAI domain in understanding municipalities' inclination to undergo

	heritage-based development processes as a precondition to effectively promote the conservation and enhancement of inner areas' under-used built heritage. After a critical reading of the new challenges for planning posed by the pandemic and SNAI's role within them, the contribution moves to frame the decision support tool, focusing on inner areas' specificities. Finally, the tool's application to a case study, an inner area in Campania Region, allows to outline and discuss its possible benefits to SNAI implementation and its limits, as well as its integration possibilities with other methodologies from an inclusive and participative perspective toward decision-making.
Title	**Multi-criteria analysis for identifying suitable sites for multi-purpose artificial reservoirs**
Author(s)	Matteo Masi (University of Firenze) Chiara Arrighi (University of Firenze) Fabio Castelli (University of Firenze)
Abstract	Due to water scarcity, climate change, and a growing population, there is a pressing need for improved water resources management practices. In particular, increasing water storage with the construction of new artificial reservoirs is crucial in addressing these challenges, to meet the community's requirements for drinking water, energy, irrigation, and flood risk mitigation. While the geographical locations of the reservoirs can be evaluated on a merely topographic basis, there are other essential aspects, usually in conflict with each other, that need to be taken into account in order to identify the candidate sites, such as bio-physical, socio-economic, regulatory, and environmental factors. In this work, we present a methodology, based on multi-criteria decision making (MCDM), for identifying the optimal locations for new reservoirs while simultaneously considering all the aspects above. The developed framework is subdivided into two steps. In a first step, an algorithm automatically analyses a large number of sites based on a Digital Elevation Model (DEM). For each site it optimizes the location and orientation of the dam and calculate the geometrical characteristics, such as the dam length, dam volume and the water storage volume. In a second step, a MCDM analysis is performed to rank all the potential sites. The selection criteria are defined quantitatively, based on a territorial analysis combined with hydrological modelling. The criteria include: geometric and morphological aspects (reservoir volume, etc.), hydrological indicators (water balance, potential flood mitigation), anthropization (population, infrastructures, etc.), landscape,

	archaeological heritage, ecology, environmental components and natural hazards. A web-based survey platform was developed to involve all the stakeholders in the decision-making process, by collecting their opinions on the relative importance of each individual criterion. We present the application of the developed methodology to a case study in the Arno river basin, Italy.
Title	**A spatial composite index for landscape strategic assessment**
Author(s)	Sebastiano Barbieri (Politecnico di Torino) Caterina Caprioli (Politecnico di Torino) Marta Bottero (Politecnico di Torino)
Abstract	Landscape is a multifaceted issue that involves not only ecological but also environmental, social and economic values, and the presence of different actors (public government representatives, planners, citizens, developers and owners). In this context integrated approaches are required for supporting landscape planning, design and management. Moreover, when dealing with landscape systems, the analysis of the geographical patterns of the elements under investigation plays a fundamental role. The paper proposes an innovative approach for supporting landscape strategic assessment based on the integration of Geographic Information Systems (GIS) and a specific Multicriteria Analysis technique, named Analytic Hierarchy Process (AHP). Starting from a real case related to the Landscape Plan of Piedmont Region, the present paper considers the construction of a composite spatial index based on the combination of several indicators, such as soil consumption, hydrogeological risk, naturalness, to name a few. The contribution illustrates the development of the evaluation procedure and the final results in terms of synthetic maps able to visualize the outcomes of the analysis and to monitor landscape transformation over time; furthermore, the synthetic maps can be helpful for easing the communication with the different stakeholders involved in the decision-making process related to the definition and assessment of future development strategies for landscape development and management.
Title	**Mapping and Bundling Ecosystem Services for Spatial planning with the AHP technique. A Case-Study in Tuscany (Italy)**
Author(s)	Massimo Rovai (University of Pisa)

	Tommaso Trinchetti (University of Pisa) Francesco Monacci (University of Pisa)
Abstract	Agricultural and forest ecosystems provide multiple ecosystem services (ESs) fundamental to the well-being and quality of life of citizens. However, in the European context, these ecosystems are often threatened by processes of urban development, around cities, or abandonment, in mountainous or remote areas. Faced with the need for solutions oriented towards greater sustainability and resilience of socio-ecological systems, planning should contribute to rebuilding more integrated and mutually beneficial relationships between urban and rural areas, ensuring the effective production of multiple ESs. The regulation and management of ESs are complex and require scientifically sound and widely understandable policies and governance models, based on detailed assessment methods. The availability of spatially explicit information is particularly important in the design and implementation of plans and policies for ES management. Many approaches and methods for mapping ESs have been developed, ranging from the simple use of land use and land cover (LULC) maps to dynamic process-based models. We propose a method for mapping the supply of five ESs produced in agricultural and forest areas, based on the processing of open-source territorial data through the analytic hierarchy process (AHP), and tailored for the Tuscany region (Italy). The method integrates the LULC map with other data to obtain a comprehensive ESs assessment, and then uses cluster analysis to identify bundles of ESs. The AHP allows to develop a method for ES mapping that, from a methodological point of view, is not as resource intensive as many models but, at the same time, can be more comprehensive and specific than only using LULC maps. We present the results of the application of the method to the territory of the Municipality of Lucca. Based on the first trials, the method seems to show high potentialities as a Decision Support System to promote innovative governance models for ES management.

1.3 Urban greening

In the face of accelerating environmental challenges, urbanization pressures, and the increasing impacts of climate change, there is a growing need for planning strategies that are not only sustainable, but also resilient and adaptive. Nature-Based Solutions and the broader integration of ecosystem services into urban development are gaining prominence as holistic approaches that address social, environmental, and economic objectives simultaneously (Babí Almenar et al., 2021). However, the complexity and multi-dimensional nature of these strategies call for robust tools that can guide decision-makers through nuanced evaluation processes. MCDA provides a structured way to capture the various dimensions of value—ranging from biophysical benefits and cost efficiency to social and cultural impacts—that are often inherent in projects aimed at enhancing urban resilience and ecological health. Whether assessing green infrastructure initiatives or evaluating the contribution of ecosystem services to urban wellbeing, MCDA can help ensure that policy and planning decisions are informed, transparent, and aligned with broader sustainability goals. For instance, as shown by the study from Oppio et al. 2024, the combination of value-based methods with cost-based methods might provide more robust and valid results. The following contributions highlight how MCDA methodologies can be adapted and applied to support the evaluation of nature-based and ecosystem-driven strategies, offering insights into how these tools can foster more livable, resilient, and ecologically integrated urban environments.

Title	**A methodological framework to assess Nature-Based Solution (NBS) through Multicriteria Analysis (MCA)**
Author(s)	Giulia Datola (Politecnico di Milano) Alessandra Oppio (Politecnico di Milano)
Abstract	Urban and territorial systems are exposed to multifaceted and multidimensional shocks and stresses, both natural and man-made. Various policies and actions have been undertaken at different levels from international to national (National Recovery and Resilience Plan) to find tangible solutions to make cities, territorial systems, and communities able to respond and resist such pressures. Nature-Based Solutions (NBS) have gained great relevance and interest, among different actions. NBS are currently implemented in urban and territorial systems to address and solve multifaceted issues concerning social, environmental, and economic dimensions. Therefore, NBS design and implementation are both a challenge and an opportunity to overcome multidimensional aspects. According to this interest, an important task has to be fixed, or rather, the necessity of the appropriate assessment tool able to evaluate NBS according to their complexity and multidimensional challenges of implementation, to properly support the decision process. In the literature, Multicriteria Analysis (MCA) are widely explored and applied to address complex and multidimensional decision process. However, the application of MCA for NBS strategies assessment is quite limited. This research aims at proposing a methodological framework to assess NBS strategies through MCA. Firstly, this contribution provides a set of multidimensional criteria, concerning society, environment, and economic dimensions. Secondly, the

	research proposes the application of the Simple Multi-Attribute Rating Technique Extended to Ranking (SMARTER) method to rank different criteria. This application aims at addressing and testing SMARTER effectiveness and suitability to assess the importance of multidimensional criteria, in order to support and facilitate a participatory and multidimensional evaluation process for NBS implementation strategies.
Title	**A multidimensional evaluation framework to assess the Ecosystem Services provided by green roofs**
Author(s)	Alessandra Oppio (Politecnico di Milano) Caterina Caprioli (Politecnico di Torino) Marta Dell'Ovo (Politecnico di Milano) Marta Bottero (Politecnico di Torino)
Abstract	Ecosystem Services (ES) have been defined as the benefits that humans derive from nature (Millennium Ecosystem Assessment - MEA, 2005), including food, fibre and fuel provision, climate regulation, air and water purification, flood protection, soil formation, nutrient cycling, recreation benefits, to name a few. The notion “ecosystem services” has pointed out its role in reinforcing the societal value of nature’s and landscape’s functions and nowadays are at the centre of green cities’ policies and strategies tackling the challenges of sustainability. In Europe, in fact, more than 70% of the population is already living in urban areas, and this number is still rising. Within this context challenges for sustainable development will be more concentrated in cities and urban green spaces since considered as having an essential role in contributing to policy objectives for sustainable urban development, such as improving public health, preserving biodiversity, reinforcing social cohesion, supporting the economy, providing opportunities for recreation and helping cities adapt to a changing climate. Landscaping rooftops and courtyards are some of the strategies for creating new natural spaces and increasing the presence of green infrastructures in the cities. The present contribution aims at evaluating green roofs according to an ecosystem perspective, by considering the evidence of their benefits on inhabitants’ wellbeing, their ability to mitigate climate change and to preserve biodiversity. An integrated evaluation model is proposed to take into account the different dimensions of value in the study of Ecosystem Services (ESs) and to support decision makers (DMs) in the definition of actions able to increase the quality of life in cities. The proposed methodology evaluates the biophysical and economic values provided by ESs, by integrating cost-based (initial, maintenance

	and operating costs) and value-based approaches (socio-cultural values through Multicriteria Decision Analysis). The integrated framework is applied for the analysis of the overall values produced by a project of a green roof in the city of Turin (Italy).

1.4 Risk and emergency

In contexts marked by high uncertainty—whether due to natural hazards such as floods or socio-political crises such as armed conflict—the ability to make strategic decisions in informed and timely way becomes not only essential but lifesaving. Urban systems and territorial infrastructures, when subjected to such shocks, require not only immediate response but also long-term strategies for resilience and continuity. MCDA offers a vital tool in these situations, enabling the integration of diverse knowledge domains, stakeholder values, and competing priorities into structured and transparent decision-making processes. Its application is particularly significant when traditional quantitative data is limited or when multiple conflicting dimensions of value must be weighed against one another.

Whether applied to the spatial assessment of flood risk in a major European river basin or to the urgent planning of emergency facilities in war-affected urban regions, MCDA methods demonstrate the capacity to synthesize expert knowledge, stakeholder input, and geospatial information into actionable outcomes. The following contributions present methodological innovations and practical applications of MCDA for spatial planning under conditions of stress, shedding light on the versatility of these tools in navigating complex and multidimensional planning challenges.

Title	**Flood damage assessment and mapping: the MOVIDA project**
Author(s)	Alberto Colorni (Poliedra-Politecnico di Milano) Daniela Molinari (Politecnico di Milano) Simona Muratori (Poliedra – Politecnico di Milano) Paola Tresca (Poliedra – Politecnico di Milano)
Abstract	MOVIDA is the Italian acronym for Modello per la Valutazione Integrata del Danno Alluvionale, i.e. model for the integrated assessment of flood damage. The objective of the MOVIDA project was to provide-in accordance with The European Floods Directive (2007/60/EC)-an Information System able to perform an analytical evaluation and mapping of the expected damage in the Po River District, overcoming the limitations of previous maps, where the evaluation of risk remained highly qualitative and subjective. Proper damage assessment tools were identified

	for the five macro-categories of exposed elements included in the Floods Directive: population, infrastructures (roads and railways, strategic buildings), environment and cultural heritage, economic activities, hazardous installations. In this work, we present the Multi Criteria Analysis methodology we used to compute and visualize on a map through a GIS the expected damage in the considered areas, according to color classes representing different levels of expected damage. The damage assessment was synthesized into four main attributes: Monetary damage, Exposed people, Damage to cultural heritage, Damage to transport network. Subsequently, the Electre Tri rating methodology was employed to assign each territorial unit (census geographic unit) to a class of expected damage. To determine the weights of the different attributes, that reflect the value system of the decision maker, 16 experts were interviewed through a questionnaire. An analysis was conducted to investigate the sensitivity of the results to variations in the weights, showing that in most Territorial Units the classification is quite robust.
Title	**Continuity, transformation, sustainability: a framework to design and evaluate emergency scenarios for the city of Kharkiv (Ukraine)**
Author(s)	Vanessa Assumma (University of Bologna) Francesco Pittau (Politecnico di Milano) Lidia Bernasconi (Politecnico di Milano) Alice Ghezzi (Politecnico di Milano) Elisabetta Valsecchi (Politecnico di Milano)
Abstract	The present contribution illustrates an academic and educational experience focused on addressing sustainability and resilience in emergency scenarios, that are threatened by socio-political conflicts. The aim of this work is to develop a multi-level assessment framework able to address continuity, transformation, and sustainability in conflicting contexts and to deliver an emergency response project. The problem under investigation is tackled by considering a real case study, that is the city of Kharkiv (Ukraine). Two Multicriteria Decision Analysis techniques (MCDA) are identified to support rational and shared choices along the evaluation process and design phases. An Analytic Hierarchy Process (AHP), which allows for a rational breakdown structure of the problem, is adopted within a localisation study. A set of criteria are identified through an investigation of emergency facilities conceived as best practices. These are then compared with respect to the facilities to select the one closest to the project. Parallelly, a Simple Multi-attribute Rating Extended to Ranking (SMARTER) ranks the relevance of a set of criteria

representing the characteristics of emergency response structures. Finally, the evaluation process is carried out, involving both local stakeholders and specialists, with expertise in emergency, spatial planning, building construction and neuroscience.

The twofold evaluation approach would overcome the issue of a limited amount of information due to conflict emergency conditions and substantiate the most suitable solution.

The MCDAs have brought concrete results from the point of view of the choice of the project area and of the characteristics of the structure, thus providing a reliable decision support for the project design.

The contribution also reflects on the role of decision support systems to tackle complexity and uncertainty, according to a multi-level and spatio-temporal approach, while opening to future transdisciplinary research directions.

1.4 Urban sustainability assessment

Urban development today must navigate the simultaneous pressures of environmental sustainability, technological innovation, economic competitiveness, and social wellbeing. As cities strive to become smarter and more sustainable, public institutions, researchers, and practitioners are increasingly turning to MCDA methodologies as critical tools for structuring complex decisions. By incorporating quantitative and qualitative indicators, stakeholder values, and participatory inputs, MCDA enables more transparent, replicable, and context-sensitive decision-making. Specific applications of MCDA methods underpinning their potential for sustainability assessment are numerous. Oppio et al. (2021) integrate GIS and MCDA to evaluate the quality of urban open spaces, Carli et al. (2018) propose a set of performance indicators using MCDA techniques to analyse the sustainable development of metropolitan areas in terms of energy, water and environmental systems. Similarly, Stanković et al. 2021 propose a model for overall sustainability assessment of port regions.

The following contributions further reflect the versatility and relevance of MCDA methods across a spectrum of spatial and policy-related challenges. From evaluating smartness and urban quality of life across European cities, to mapping sustainability in maritime port regions, to structuring transparent and efficient public procurement systems, and finally, to supporting early-stage renewable energy community design in dense urban areas—each study leverages techniques such as VIKOR, PROMETHEE, entropy-based weighting, and MOO-MCDM integration. Together, they demonstrate how MCDA is not only a methodological choice, but a strategic asset in guiding sustainable transformations at various territorial scales.

Title	**Quantifying Smartness and Urban Development in European Cities**
Author(s)	Ivana Marjanović (University of Niš) Žarko Popović (University of Niš)
Abstract	In contemporary contexts, urban areas have emerged as primary drivers of economic expansion and affluence. The rapid and extensive proliferation of urban centers over recent decades has given rise to a critical concern regarding their durability, coupled with escalating issues concerning infrastructural, ecological, and societal dimensions. In response, the concept of smart cities has emerged as a prospective solution, aiming to bolster the competitive edge of local communities and urban zones. This is achieved through the strategic implementation of pioneering technological innovations, orchestrated to enhance the quality of life for citizens by optimizing public services and cultivating a more salubrious environment. The principal objective of the present study entails a comprehensive evaluation and classification of European cities, contingent upon indicators that gauge their adeptness in both the smart city paradigm and urban advancement. To achieve this, an analytical framework is devised, drawing upon data procured from four successive iterations of Eurostat's Urban Audit Perception Survey, spanning the temporal expanse from 2009 to 2019. The dataset encompasses perceived urban performance metrics, as assessed by residents domiciled within these urban agglomerations. This evaluative schema encompasses multifaceted dimensions of urban sustainability and development, encompassing economic, social, environmental, and governance facets. Notably, citizens' perceptions of the quality of life within their respective urban environs are deemed invaluable informational substrates. This primary data source serves as the bedrock upon which targeted enhancements in urban performance are predicated, particularly in domains perceived as deficient by inhabitants. To underpin the scrutiny of diverse attributes germane to urban performance, a composite model embracing multiple criteria is engendered. The construction of this model integrates entropy analysis to ascertain the relative weights of these criteria. This amalgamation is complemented by the application of VIKOR (VIšeKriterijumska Optimizacija I Kompromisno Rešenje), a multi-criteria optimization and compromise solution methodology, to facilitate the ranking of cities. Respondents' subjective inclinations are captured through a quantified interpretation of their responses, marked on a 4-point Likert scale. This quantification of qualitative data substantiates the analytical processes. The instantiated multi-criteria model in this scholarly discourse encompasses a diversified assemblage of 28 discrete criteria, each bearing approximate

	commensurate significance. These criteria are methodically organized into six overarching categories. The study encompasses a dynamic sample set, with the number of European cities under observation spanning from 73 to 111, contingent upon the sample sizes inherent to each research iteration. The culminating outcomes of the ranking exercise are presented visually, providing insights into the geographical locales within Europe where residents perceive the highest echelons of smartness and sustainable urban evolution. A pivotal observation emerging from this research is the preponderance of Western European cities, predominantly concentrated within the United Kingdom, amid the upper echelons of the ranking. It is pertinent to acknowledge that, apart from a select few such as Vienna, Luxembourg, Copenhagen, and Stockholm, the remaining scrutinized capitals do not consistently feature within the top decile across the observed years.
Title	**Advancing Sustainability Assessment in Port Regions: Utilizing an MCDM Approach for Composite Index Development**
Author(s)	Jelena J. Stanković (Faculty of Economics, Niš) Saša Drezgić (Univeristy of Rijeka)
Abstract	Maritime transportation and ports constitute pivotal conduits within the intricate web of global economies, facilitating the exchange of more than 90% of commodities in international trade. The profound economic significance of maritime transport casts a substantial influence on the societal fabric and environmental equilibrium of port regions. The present study endeavors to forge composite indices, which stand as salient, empirically-grounded instruments employed to juxtapose and oversee diverse facets of sustainability across 37 maritime port regions spanning seven countries along the European periphery of the Mediterranean. This comprehensive analysis envelops a quinquennial span from 2014 to 2018. The devised model enshrines a corpus of data gleaned from Eurostat and OECD repositories, encompassing annual data at the NUTS2 territorial level. This expansive dataset encapsulates the triad of economic, social, and environmental dimensions that collectively form the bedrock of sustainability considerations. Notably, within the cohort of economic indicators, pivotal emphasis is laid on two pivotal markers of maritime activity: the transport of goods and the conveyance of passengers across maritime domains. In the creation of these composite indices, an intricate framework underpinning multicriteria decision-making (MCDM) was harnessed. This approach seamlessly interweaves the entropy methodology within the weightage schema, harmonizing it with the Preference Ranking Organization

	METHod for Enrichment of Evaluations (PROMETHEE) as the quintessential mode of aggregation. The culmination of this analytical framework culminates in a nuanced panorama that illuminates the intricate tapestry of sustainability across these maritime port regions. The findings bring into stark relief two salient indicators, namely GDP per capita and population density, as the preeminent barometers of relative importance in the realm of port region sustainability. The discerned ranking outcomes furnish a fascinating tableau, wherein Attica emerges as the apical region in terms of holistic sustainability assessment. Notwithstanding this, it is intriguing to observe that the preponderance of top-tiered port regions are concentrated within the geographical confines of Italy, Spain, and France.
Title	**Evaluation of the most economically advantageous tender in public procurement procedures: the main evidences provided by the multi-criteria decision-making approaches**
Author(s)	Debora Anelli (Polytechnic University of Bari) Pierluigi Morano (Polytechnic University of Bari) Francesco Tajani (Sapienza University of Rome) Tiziana Acquafredda (Polytechnic University of Bari)
Abstract	The European Commission within the “Europe 2020” strategy has considered the public procurement as one of the vital market-based policy approaches for the achievement of a smart and sustainable development of the European economy. However, the management of the public procurement procedures is often difficult: choosing the most suitable criteria for achieving the aims of the urban intervention by evaluating the suppliers, being coherent with the European regulatory framework for the sustainable development, carrying out a transparent and clear assessment procedure are only some of the most critical issues related to the public procurement system of the urban development. Due to the multidimensional nature of the projects’ selection, several multi-criteria decision-making approaches have been developed for giving an ordered methodological structure, rather than a supporting guideline to the operators involved in the public procurement process. The aim of the work is to provide a systematization of the existing scientific literature on the applications of the multicriteria decision making approaches in order to identify: i) the most used multi-criteria technique for each of the public procurement step, ii) the most considered type of criteria for the tenders evaluation, iii) the main advantages and disadvantages of each multi-criteria technique, iv) the main future

	insights of the research field in order to highlight the cogent needs for improving the public procurement system with the help of the multi-criteria decision-making approaches. The achieved results suggest interesting and useful issues, especially for the weighting of the criteria, the construction of the final ranking of the suppliers and the integration of multi-criteria techniques, by giving the possibility to improve the existent knowledge on the public procurement field.
Title	**A Multi-Criteria Tool for Urban Renewable Energy Community Projects**
Author(s)	Sibilla Ferroni (Politecnico di Milano) Francesco Causone (Politecnico di Milano)
Abstract	Renewable energy community (REC) models play a vital role in the energy transition, aiming to decarbonise the built environment by promoting energy retrofit interventions and accelerating the deployment of on-site renewable energy sources. However, designing these communities present multifaceted challenges, especially in urban areas with high density of population and limited space for renewables. Here, effective decision-making is essential but hindered by the lack of a reference design framework and evaluation criteria. In Europe, local authorities (LAs) are pivotal in implementing REC models, particularly in the initiation phase. At this stage of the design, LAs seek to evaluate the feasibility of REC implementation in their territory, considering environmental, economic, and performance objectives simultaneously. To address this challenge, the presented work discusses the development of a tool to support LAs in the early design stages of REC in urban contexts. The proposed tool aims to provide LAs with a quantitative approach capable of addressing multiple and conflicting objectives. Therefore, the tool will be based on the complementary relationship between multi-objective optimisation (MOO) models and multi-criteria decision-making (MCDM) methods. The MOO model focuses on finding a diverse set of efficient solutions, highlighting the trade-offs between conflicting objectives, while MCDM is adopted to provide a framework to evaluate and compare these solutions based on the stakeholder's preferences. By integrating MOO and MCDM, the tool will enable LAs to explore a range of viable solutions for REC design while considering various criteria simultaneously. This approach allows decision-makers to make informed choices aligned with their priorities and objectives.

1.5 Sustainable mobility

Achieving sustainable and decarbonized mobility systems is a central objective for both national and local governments in the broader pursuit of climate neutrality and urban resilience. Among the wide array of strategies available, the transition to low- or zero-emission public transport fleets and the expansion of soft mobility infrastructures—such as bike-sharing networks—represent two high-impact interventions. However, both present complex decision-making challenges that require careful balancing of environmental, financial, technological, and spatial considerations. In this context, MCDA emerges as a valuable tool to guide informed, transparent, and context-sensitive planning decisions.

The contributions summarized here exemplify how MCDA can support sustainable transportation strategies. The first study presents a life-cycle-based MCDA framework to evaluate various fleet renewal scenarios for local public transport systems in Northern Italy, highlighting the feasibility and trade-offs of clean vehicle technologies in urban and ex-urban contexts (Coppola et al., 2023). The second study focuses on optimizing the spatial deployment of bike-sharing stations in Vienna, Austria, emphasizing not only typical mobility and accessibility indicators, but also the role of shared mobility in enhancing transportation network robustness in the face of disruptions. These applications demonstrate the growing relevance of MCDA in shaping next-generation transport systems that are both environmentally sound and resilient to future challenges.

Title	**Multi-Criteria Life-Cycle Assessment of Local Public Transport fleets renewal**
Author(s)	Pierluigi Coppola (Politecnico di Milano) Marco Bocciolone (Politecnico di Milano) Emanuela Colombo (Politecnico di Milano) Francesco De Fabiis (Politecnico di Milano)
Abstract	Among the strategies to achieve the goal of transport decarbonization, national and local government have been funding the renewal of local public transport (LPT) fleet through either the acquisition of new clean vehicles or the introduction of advanced clean (bio-)fuels. In order to optimize the investment over time and avoid undesirable indirect counter-effects, such policies need to be assessed ex ante and duly planned. In this paper, a methodology based on a life-cycle assessment of (investment, maintenance and operating) costs and (global and local) environmental impacts is proposed to identify suitable pathways for renewal of the existing bus fleet, in the medium and long term. Using a multicriteria decision matrix, different a-priori scenarios are compared, seeking for non-dominated ones with respect to financial

	and environmental sustainability criteria. The methodology has been applied to the case of the Como, Lecco, and Varese provinces (with about 860 operating buses, almost all equipped with diesel engines and operating in both the urban and the ex-urban context). In the urban context, the study has shown that the "full-battery-electric" scenario has the lowest environmental impact since there are zero tailpipe emissions and greenhouse gases are lower than all the other transition scenarios. For the ex-urban service (characterized by medium- and long-distance routes), a "full-battery-electric" scenario is not yet feasible, considering that long-range electric buses having sufficient battery autonomy to guarantee efficient operations in these contexts are not yet widely available. Liquefied natural gas-powered and hybrid electric vehicles would be other options for decarbonising ex-urban LPT, but their life-cycle impacts should be considered with care.
Title	**Implementing New Bike-Sharing Stations in Urban Areas: a Multi-Criteria Approach**
Author(s)	Michele Rabasco (University of Bologna) Caterina Malandri (University of Bologna) Roberto Patuelli (University of Bologna) Aura Reggiani (University of Bologna) Rebecca Rossetti (University of Bologna)
Abstract	Bike-sharing systems are attracting considerable interest in the literature for their potential key role in encouraging the transition from car-based private transportation to more sustainable mobility. This paper aims to guide decision-makers in solving the problem of choosing the most suitable places – in urban areas – to implement new bike-sharing stations. Since that is an optimization problem, we use multi-criteria analysis (MCA) to provide a ranking of possible alternative locations. The set of alternatives considered is a subset of public transportation stations where bike-sharing is not provided. The hypothesis behind this choice is that, given the complementarity between public and shared transportation, implementing new bike-sharing stations near public transportation stations would promote the use of bike-sharing. The criteria considered are derived from the literature (Bahadori et al. 2021). Among them, there is the structure of the bicycle network (number of stations, network capacity, etc.) and the city structure (city size, points of interest, active population, etc.). The contribution of this paper is including in the analysis a feature that has been less studied in the bike-sharing literature, i.e., its ability to promote urban transportation robustness. The potential of bike-sharing in promoting the robustness of a transportation network is relevant in the case of disruptive

	events. We focus on the robustness of urban public transport networks, in structural terms (network properties and travel times) and in terms of passenger use (Zhang et al., 2019). The scenarios were identified by a group of experts on the topic of sustainable mobility as part of the SmartHubs project. To illustrate our approach, we apply MCA to some suburban districts in the cities of Vienna, Austria, in which there is a lack of bike-sharing stations. This case study represents a prototype for further applications to different cities in the European Union.

1.6 Climate policy

Several types of current decision-making problems relate to the climate mitigation and development umbrella. In many cases, decision-makers must also grapple with uncertainty in climate projections, the distributional impacts of mitigation policies, and the need to ensure just transitions for affected populations. Examples range from urban planning decisions aimed at reducing emissions, to agricultural policies that must balance productivity with resilience to climate impacts. MCDA approaches can provide effective contributions to strengthen the credibility and implementation of climate policy (Cohen et al. 2018).

This contribution proposes a multi-objective decision-making framework to identify efficient emission reduction strategies in the Po Valley. By employing a surrogate model based on neural networks—trained on outputs from the CAMx chemical-transport model—the approach enables rapid evaluation of policy scenarios across the agricultural and energy sectors. The framework incorporates not only air quality improvements, as captured by reductions in average PM2.5 concentrations, but also quantifies associated health impacts and external costs, offering a comprehensive evaluation of potential measures. This study underscores the critical role of agriculture in regional air pollution and highlights the necessity of incorporating cross-sectoral strategies in environmental planning through advanced multi-objective modelling.

Title	**Multiobjective analysis of the impact of agro farming on air quality and GHG emissions in the Po Valley**
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Abstract	The Po basin area is well-known for its high levels of air pollution, mainly fine particulate matter (PM2.5), which comprises secondary fractions produced by precursor gases. A relevant portion of such precursors are emitted by intensive livestock farming and industrial agriculture which also produce climate-altering gases like methane (CH4) and nitrous oxide (N2O). A multiobjective problem is defined to identify efficient policies to improve air quality at the lowest possible emission reduction cost. The air quality is encapsulated into a single index representing the annual average of PM2.5 over the entire domain of Northern Italy, strictly related to human health damages. The solution of such a multiobjective problem is made possible by using a surrogate model to estimate the variation of PM2.5 concentration for different emission reduction decisions. This study uses neural networks to represent such a link in a computationally efficient way. The neural networks were trained using a set of emission scenarios simulated with the CAMx deterministic chemical-transport model. The multiobjective problem is solved under different settings. We first assume that emission reduction measures pertain only to the agricultural sector, and then that they can be coupled with energy and technical measures in all sectors. Additionally, PM2.5 concentrations can be transformed into health damage to the resident population and summed to the value of reduced GHG emissions to provide a full estimation of external costs. The results of the study highlight the significant impact of the agricultural and livestock sectors in the Po Valley and the importance of including the related policies in developing local air quality and carbon emission reduction plans.

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