Multiple Criteria Decision Making

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Multiple Criteria Decision Making for Sustainable Development

Pursuing Economic Growth, Environmental Protection and Social Cohesion

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Multiple Criteria Decision Making

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Preface

Interest in sustainable development has increased over recent years. As originally highlighted in the Brundtland Report (1987), sustainability requires a balance between environmental concerns, the economy, and social development. However, over the years, there has been an exponential increase in economic activity and high levels of consumption, which have hindered long-term planning and made sustainable management across different areas more difficult. It has therefore become increasingly necessary to combine the interests of the various stakeholders involved in—or affected by—long-term planning measures, in order to achieve a balance between their needs, those of the environment and future generations, and the need for economic development.

It is worth noting, however, that decision problems have been complicated by an ever-greater degree of complexity, forcing decision-makers to seek out new approaches and methodologies that facilitate the processes that support decision-making (Ferreira et al., 2019). In this regard, MCDM and MCDA are now well-known acronyms for multiple-criteria decision-making and multiple-criteria decision analysis, respectively, and although epistemological differences exist between these two branches of operational research/management science (OR/MS), both share a focus on decision aid (Keeney, 1992; Belton & Stewart, 2002).

The application of MCDM/A methods has grown exponentially over the past few years, leading to a change in the decision-making arena in general (Zavadskas et al., 2014; Carayannis et al., 2018). MCDM/A approaches are particularly well suited as supporting tools in strategic and operational decision-making related to sustainable development. MCDM/A contributes to all phases of the decision process, starting from problem structuring and decision modeling up to the formulation of recommendations and the implementation phase. This is particularly important, given the multifaceted and complex nature of sustainability, as well as the ill-defined character of many decision problems in this area. Such features call for holistic approaches to sustainability decision-making, which cover not only all aspects of the problems but also the preferences of all stakeholders.

In the light of the relevance of MCDM/A for sustainability problems, the aim of this edited volume is to present recent developments and methodological contributions related to the design and implementation of MCDM/A approaches for economic development, social cohesion, and environmental sustainability.

Organization

The book includes 10 contributions covering applications of MCDM/A methodologies in various areas related to sustainable development, covering issues related to strategic and operational decisions at the macro- and micro-levels.

The first three chapters of the book cover the basic concepts of sustainability and its measurement at the macro-level. The book starts with the chapter by Diaz-Balteiro and Romero, in which the authors analyze the conceptual and operational links between the sustainability issue and the MCDM/A theory. The chapter also highlights several important issues about the use of an "indicators approach", which is commonly employed in the framework of MCDM/A for measuring sustainability.

The second chapter by Kartsonakis, Grigoroudis, and Zopounidis presents an application of an outranking MCDA approach, namely the ELECTRE TRI method, to assess country energy sustainability performance. Results are presented for 119 countries, following the framework of the Energy Trilemma Index by the World Energy Council.

In the third chapter, Koasidis, Karamaneas, Kanellou, Neofytou, Nikas, and Doukas present a multi-criteria group decision analysis framework, combining the TOPSIS method and the 2-tuple linguistic representation model, to capture European climate stakeholders' perceptions of the urgency to integrate sustainable development goals in scientific support of climate policy design that is based on climate- and energy-economy modeling.

The fourth chapter of the book by Antunes discusses the added value that multi-objective optimization models and MCDA methods provide to support the decision-making process in energy systems planning. The chapter focuses on problems related to the issue of providing affordable, reliable, sustainable, and modern energy for all, which is one of the Sustainable Development Goals in the 2030 Agenda for Sustainable Development adopted by the United Nations in 2015.

In the next chapter, Gonzalez-Urango, Mu, and García-Melón provide a comprehensive overview of the literature on the applications of the analytic network process (ANP) as a tool for strategic planning in sustainable territorial urban development. The critical analysis of the relevant literature highlights the best practices on the use of ANP in this area, and recommendations are provided for researchers and practitioners.

The sixth chapter by Norese, Corazza, and Cottafava describes the experience from the use of a multicriteria modeling approach for the analysis of the social and economic impacts of a major infrastructure railway project in Italy. Multicriteria methods and models that can facilitate the implementation of counterfactual analysis on areas affected by the project are discussed.

In the next chapter, Weck, Humala, Tamminen, and Ferreira present a holistic framework for the determination of the conditions and practices that facilitate and encourage knowledge collaboration and knowledge sharing between regional stakeholders engaged in building age-friendly smart living environments. The framework is developed in the context of a case study involving a region in Finland, and the use of MCDA structuring methods and techniques is discussed, such as strategic options development and analysis (SODA), cognitive mapping, nominal group technique (NGT), and multi-voting.

The eighth chapter by Popovic, Meidutė-Kavaliauskienė, Stanujkic, and Karabasevic presents the application of a multicriteria methodology for supporting the decision process in a construction project in the tourism sector, based on a sustainability framework that considers economic, ecological, and social aspects. The methodology is applied to a case study involving the construction of a hotel in Serbia.

In the next chapter, Renna, Carlucci, and Materi consider an assembly job-shop scheduling problem. The authors present a decision-making model to release the orders in the shop floor to improve customer satisfaction and the performance of the production system. Simulation results are presented to evaluate the model and the obtained results.

The book closes with the chapter of Eskantar, Doumpos, and Zopounidis, who present a financial analysis of the environmental, social, and governance (ESG) performance of Greek companies. The evaluation is based on the PROMETHEE II multicriteria method using a set of commonly used financial ratios. Empirical results are presented for 29 large Greek companies that employ the principles of ESG.

By demonstrating MCDM/A methods' potential and role as aid to decision-making in the fields of sustainability and sustainable development, we believe this book will alert management practitioners, policymakers, and researchers to the theoretical developments and practical applications of these methodologies.

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In Search of a Scientific Research Programme for Addressing the Sustainable Management of the Environment

Luis Diaz-Balteiro and Carlos Romero

Abstract Since its origin in the eighteenth century, in the forestry field, the concept of sustainability has evolved considerably by increasing its level of complexity. This increase in complexity is due mainly to the integration of the concept and measurement of the degree of sustainability of a natural system into a multifunctional context. Besides this, the degree of complexity has become higher due to the incorporation of the preferences of several segments of society towards the different functions or uses provided to it by the environment and its embedded resources. Following results given in a recent and extensive literature, it has been advocated that a fertile way of addressing the sustainability issue in this current context consists of characterizing the different functions supplied by the environment by a battery of indicators of different natures. After that, the "indicators approach" is embedded in the well-known and widely-used multiple criteria decision-making theory. Following in this direction in this paper it is analytically proposed that this merge could underpin the "hard core" of a "Scientific Research Programme" for successfully resolving these types of problems. The paper also highlights aspects related to the use, and sometimes abuse, of the "indicators approach". It also discusses the potential connections between the so-called circular economy and the sustainability issue within an environmental management context.

Keywords Circular economy · Indicators · Multi-functionality · Multiple criteria decision making · Scientific research programmes · Sustainability

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1 Introduction

It is widely accepted that one of the main challenges faced by current societies consists of the development of a scientific conceptual framework for dealing operationally with the sustainable management of the environment and its embedded natural resources. Although important steps have been taken in the right direction, nowadays this new theoretical framework which, from an epistemological perspective could be considered a Scientific Research Programme (SRP), in a Lakatosian sense, is far from being fully achieved or, above all, accepted by the several institutions forming current democratic societies. It should be noted that, throughout this paper, the concept of SRP is used rather laxly and intuitively. However, for readers interested in the theoretical aspects of this structure, an appendix can be found at the end, in which the basic features of an SRP are presented, as well as providing some key bibliographical sources. In any case, in our view, the hard core, as well as the positive heuristics of the SRP, for successfully handling sustainable environmental management issues should be supported by a plurality of scientific theories, which implies the convergence of knowledge flowing from many disciplinarian fields like: computational sciences, ecology, economics, epistemology, mathematics, sociology, etc. This convergence of disciplines, plus the necessary social acceptance of the SRP desired, makes its setting highly challenging.

To go deeper into the difficulties associated with the above challenge, it might be useful to distinguish between what could be called the "old" and "new" sustainability. The "old" sustainability was started in the eighteenth century in the field of forestry by von Carlowitz (1713) from a mono-functionality perspective. This orientation was followed later on by optimizing the management of other natural resources. This type of approach implicitly assumes that the environment has a practically infinite capacity to sustain the two basic functions of the environment: a source of inputs and a sink for waste. In other words, this view of sustainability has been established within what is called a linear model linking the environment and the economic systems.

This type of orientation has worked well for many years and can be conceptualized as an SRP with the following fundamental features. Its "hard core" is formed basically by the adoption of the economic marginal analysis, the concept of Paretian efficiency plus the economic concept of negative externality. The positive heuristics of this SRP involves the recruitment of mathematical techniques like Lagrangian multipliers, dynamic optimization, the use of differential equations, etc. This SRP has shown itself to be very positive for establishing rational guidelines, geared to an efficient use of the environment and its embedded resources. In the last quarter of the twentieth century, this theoretical orientation was well established in the economics field with the publication of several seminal and pioneer textbooks, forming the discipline known as "The Economics of Natural Resources and the Environment" (e.g., Dasgupta & Heal, 1970; Fisher, 1984).

This chapter is partly devoted to a criticism of the old view of sustainability, with comments on the insufficiencies of the SRP which underpins this orientation. In addition, some guidelines will be presented aimed at proposing the embryo of an extension of the above mentioned SRP that is able to accommodate most of the current social demands required in sustainable environment management. In other words, the "hard core" of a SRP, or of any other theoretical construct able to accommodate the above concerns and critical issues and, consequently, characterizing the so-called new sustainability, will require: first, to take into consideration, in quantifiable terms, the multiplicity of functions associated nowadays with the environment; and, second, to incorporate into it, in one way or another, the manner in which different segments of society or the stakeholders perceive the relative importance of these functions. The basic idea which will be developed throughout the chapter will consist of linking, conceptually and operationally, the sustainability issue to the concepts and methods of the well-known multiple criteria decision making (MCDM) theory.

2 The "Indicators Approach" and the Multi-criteria Analysis: Building the Hard Core of a SRP

A possible first step towards facing up to the above challenges and correctly performing a sustainable management of the environment and its embedded resources would consist of resorting to the so-called "indicators approach" (Rennings & Wiggering, 1997; Pannell & Glenn, 2000). According to the latter, the sustainability of a system is characterized by a battery of indicators of different natures. In many instances, the latter are grouped into three pillars of an economic, environmental and social nature, respectively. Once the indicators and pillars have been defined, the next step consists of an aggregation process of the indicators in order to obtain a final composite index, whose value is considered to be a proxy of the degree of sustainability of the system studied.

With this orientation, one crucial task will be to establish a sound and pragmatic procedure for undertaking the above-mentioned aggregation system. In this paper, and backed up by recent extensive literature (see e.g., Diaz-Balteiro et al., 2017, 2020), it is postulated that the most promising and fertile method would be to link the concept of an indicator to that of a criterion as it is used within the framework of the multiple criteria decision making (MCDM) theory. In this way, all the concepts and techniques and experiences gained from this well-known and widely used theory could be recruited as being part of the positive heuristics of an extended SRP. In fact, the main purpose of the MCDM theory consists of proposing sound methods for aggregating criteria (objectives, goals, attributes) in conflict. Thus, compromises among the criteria considered with a clear preferential interpretation are obtained.

Let us present in certain detail one of the possible adaptations of the MCDM theory to the characterization of the level of sustainability of a natural system by resorting to the "indicators approach". Thus, the main features of this orientation, following pioneer papers [14, 15], can be summarized as follows. We have $i = 1$, 2, . . ., n natural systems, whose sustainability is assessed by $j = 1, 2, \ldots, m$ indicators. The main questions can be posed in the following way:

What is the system or mix of systems with the best aggregate performance in terms of sustainability? What is the ranking of natural systems in terms of their degree of sustainability? In order to establish a sound analytical framework to solve these types of problems, the following set of variables and parameters are introduced:

R_{ij} = outcome achieved by the ith natural system when evaluated according to the jth indicator.
W_j = weight or relative importance attached by an expert or by a panel of experts to the jth indicator of sustainability.
R_j^* = optimal value of the jth indicator of sustainability (ideal value). This optimal value corresponds to the maximum value if the indicator is of the type "more is better" or to the minimum value when the indicator is of the type "less is better".
R_{*j} = worst value achieved by the jth indicator of sustainability (anti-ideal value). Obviously, this value corresponds to the minimum value if the indicator is of the type "more is better" or to the maximum value when the indicator is of the type "less is better".
K_{j} = normalising factor for the jth indicator of sustainability.
R_{ij} = normalised value achieved by the ith system with respect to the jth indicator of sustainability.
t_j = satisficing target in a Simonian sense for the jth indicator of sustainability.
p = real number belonging to the interval $[1, \infty)$ or ∞.
X_i = binary decision variables (i.e., $X_i \in [0, 1]$). X_i takes the value 1 when the ith natural system is chosen, otherwise it takes the value 0.

With the above information different realistic situations could be tackled. For instance, let us consider a situation in which an expert or a panel of experts suggests a set of satisficing targets t_j to the m indicators of sustainability considered. Within this context, the following question is crucial: what is the natural system with the highest level of achievement with respect to the aspiration levels fixed by the expert to the m indicators? As an extension to this problem, a strong or weak ordering (i.e., a ranking) of the n systems considered can be determined. The above problems can be efficiently addressed by solving the following binary weighted goal programming (GP) model (e.g., Jones & Tamiz, 2010, chapter 2):

Achievement function:

$$
\begin{aligned}
& MIN \sum_{j=1}^{m} \left(\alpha_j n_j + \beta_j p_j \right) \\
& Goals: \\
& \sum_{i=1}^{n} R_{ij} X_i + n_j - p_j = t_j \forall j \\
& Constraints: \\
& \sum_{i=1}^{n} X_i = 1 \\
& X_i = 0, 1 \forall i \\
& n_j \geq 0, p_j \geq 0 \forall j
\end{aligned}
\tag{1}
$$

The meaning of all the variables and parameters of Eq. (1) were previously defined, with the exception of deviation variables n_j and p_j which quantifies the possible under-achievement or over-achievement of the solution obtained with respect to the target values attached by the panel of experts. Moreover, we must take into account that $\alpha_j = W_j/K_j$ if the jth indicator of sustainability is of the type "more is better", otherwise $\alpha_j = 0$ and $\beta_j = W_j/K_j$ if the jth indicator of sustainability is of the type "less is better", otherwise $\beta_j = 0$. Finally, if it is aimed to achieve exactly the target value, then neither under-achievement nor over-achievement are needed?? and, consequently, $\alpha_j = \beta_j = W_j/K_j$.

By solving model (1), which computationally implies only solving a binary linear programming problem, the "most sustainable" natural system is obtained. The corresponding optimal value of the achievement function measures the corresponding degree of sustainability of that system. If we are interested in determining not only the "most sustainable" system, but also in obtaining a ranking of the n systems in terms of sustainability, we can solve model (1) iteratively. Thus, we need to solve model (1) n times, augmenting it in each interaction with an additional constraint like $X_k = 0$, when the kth natural system is optimal; i.e., the "most sustainable" one. Coherently, with this iterative procedure, the optimal values of the n achievement functions derived from each iteration quantify the level of sustainability of each one of the n natural systems considered. This model actually provides the system or the ranking of systems with the maximum aggregated achievement between the different goals considered. In other words, this solution represents "the optimal average achievement". We should be aware that this solution may give a poor performance for one or for a small set of the sustainability indicators considered. This situation within a sustainability context could be problematical. Thus, it seems of interest to also seek the "the most balanced solution", which can be obtained by minimizing the maximum discrepancy among the achievements of the different goals. This "most balanced solution" can be obtained by solving the following MINMAX Chebyshev GP model (e.g., Jones & Tamiz, 2010, chapter 2):

Achievement Function:

Min D

Subject to:

$$\left(\alpha_j n_j + \beta_j p_j\right) - D \leq 0 \tag{2}$$

Goals and Constraints of model (1).

Where variable D represents the maximum deviation; that is, the discrepancy with respect to its target of the goal most displaced with respect to the solution obtained. This type of solution seems to be an attractive one within a sustainability context, since it represents the best possible balance among criteria of different natures. However, this type of solution is not without difficulties. In fact, the "most balanced solution" obtained can provide a "poor average" which, in some scenarios, could be problematic. In short, there is a dilemma between "optimizing the average" versus "optimizing the balance". A possible way of dealing with it consists of formulating a linear convex combination of models (1) and (2), which leads, in a natural manner, to the following extended goal programming (EGP) model (Romero, 2001, 2004):

Achievement Function:

$$\text{Min } (1-\lambda)D + \lambda \sum_{\text{j}=1}^{\text{m}} \left(\alpha_j n_j + \beta_j p_j\right) \tag{3}$$

Subject to:

Goals and Constraints of models (1) and (2).

Where λ plays the role of a control parameter. In fact, for $\lambda = 1$, model (1) is reproduced, for $\lambda = 0$ model (2) is obtained. For values of control parameter λ belonging to the open interval (0, 1) we have compromises between the solution with the maximum aggregated achievement and the solution with the most balanced achievement (i.e., the system for which the indicator with the worst performance is less displaced with respect to the aggregate achievement). In short, the role of control parameter λ is something like a marginal rate of substitution trading-off "optimal average" and "optimal balance", which seem useful, in general, and especially within a sustainability context.

It is interesting to note that, computationally, all the above models represent binary linear programming formulations, which makes it easy to apply them to real problems. Some applications of this approach in the forestry field are Diaz-Balteiro et al. (2011, 2016) and Ezquerro et al. (2019).

The above approach is of a pioneering nature, but it does not aim to be of a hegemonic nature. In fact, in the last 10 years or so, practically all the methods within the MCDM theory, with their particular merits and flaws, have been applied to solve different problems associated with the sustainable environment management. Thus, in Diaz-Balteiro et al. (2017, 2020), an extensive critical review of this type of applied literature can be found. In sum, most of the approaches belonging to the MCDM toolkit can be recruited for the positive heuristics of the embryo of the proposed SRP.

Table 1 Papers using a MCDM approach for addressing the "sustainability indicators approach

METHOD	NUMBER OF APPEARANCES
Distance Functions	
Compromise Programming	2
Goal Programming	9
TOPSIS	1
Discrete Methods	
ELECTRE	2
Promethee	2
Analytical Hierarchy Process	31
Analytical Network Process	5
Data Envelopment Analysis	3
Multi Attribute Utility Theory	4
Weighted Methods	20
Other Techniques	2

Source: own elaboration from Diaz-Balteiro et al. (2017, 2020)

Thus, as Table 1 shows, there have been numerous cases resorting to MCDM models to address this problem. In fact, more than 12 different methods have been tabulated, by considering the two reviews, comprising 69 different papers focused on sustainability issues applied to agriculture, forestry, and fisheries fields. Two methods are those most used, both of them orientated towards discrete problems: Analytical Hierarchy Process, with 31 appearances, following by the weighted MCDM (Weighted arithmetic or weighted geometric mean), used in 17 papers; and both of them are found jointly in many papers. The third MCDM method frequently employed is Goal Programming, included in the MCDM distance functions for continuous cases, with nine papers. As it can be shown in Table 1, no other MCDM approach exceeds five published papers.

We would like to finish this section by recognizing that these ideas are still at a considerable distance from establishing a sound SRP. However, they would seem to be a promising outline of a "hard core" for building a theoretically sound and computationally efficient SRP for addressing problems related to the sustainable management of the environment and its embedded natural resources.

3 Potential Problems Associated with a Massive Use of Indicators

We would like to insist on the fact that the characterization of the degree of sustainability by a battery of indicators of different natures, as well as their treatment as criteria, seems to be a sound underpinning for setting up a plausible SRP. This

Table 2 Indicators included in different composite indices related to sustainability

Index	Acronym	Starting year	1st level	2º level	3rd level	scope
SAM Corporate Sustainability Assessment	CSA	1999	Dimensions 3	Criteria 20	Questions 100	61 Industries
AIChE Sustainability Index	AIChE SI	2009	Factors 7	Criteria 23	not specified not specified	Chemical Industries
ECPI EQUITY INDEX	ECPI ESG	2001	Pillars 3	Indicators 80	-- --	Multiple industries
Corporate Knights Global 100 Ranking	Global100	2005	not specified 4	KPIs 21	-- --	Multiple industries
Euronext Vigeo Eiris World 120		2012	Domains 6	Criteria 38	Indicators 330	Multiple industries
Environmental Performance Index	EPI	2006	Issue Category 11	Indicators 32	-- --	180 Countries
Urban Sustainable Index	USI	2010	Categories 5	Indicators 23	-- --	Chinese cities
Environmental Sustainability Index	ESI	2000-2005	Broad Indicators 5	Core Indicators 21	Basic Indicators 76	146 Countries

Source: own elaboration

orientation is supported by many case studies reported in the literature in the last two decades or so (Blancas et al., 2011; Diaz-Balteiro et al., 2018; Morse, 2018; Ezquerro et al., 2019). However, on analysing this extensive body of literature, one is struck by the huge number of indicators used for characterizing the sustainability of a system. Thus, it is not surprising to find specific case studies in which the number of indicators considered is over 40 (Diaz-Balteiro et al., 2017). Leaving aside the case studies, the most paradigmatic example is the Sustainable Development Goals framework (SDG), composed of a myriad of 17 goals, divided into 169 targets and 231 single indicators. Besides that, in order to quantify those indicators, some variables for each indicator are needed. It should be noted that not only the SDG framework presents serious problems for defining a composite index with all the indicators proposed (Schmidt-Traub et al., 2017; Diaz-Sarachaga et al., 2018). In fact, there are other internationally-accepted composite indices related to sustainability issues defined with a large number of indicators. All of them adopt a hierarchal structure with different names at each level (see Table 2).

SDGs represent a clear attempt to accelerate a transition towards a sustainable development at different levels of aggregation (Lyytimäki et al., 2020). However, this proposal is not lacking in difficulties. Thus, SDGs represent a normative framework with some contradictions and self-inconsistencies (Daves, 2020; Winkel et al., 2020). In addition, the SDGs' structure (high number of goals and targets) is a complicated basis for applying the "indicators approach" (Lyytimäki et al., 2020). This implies that the notion of a hierarchical structure of indicators to obtain an aggregate index is being lost since it incorporates additional dimensions into the development agenda (Adenle et al., 2020). On the other hand, Agenda 2030 recognizes that SDGs integrate the classic three pillars of sustainable development (economic, social, and environmental), although, for some authors, the economic pillar prevails over the others (Kopnina, 2021). However, Turton (2021) emphasizes the potential interest of integrating a key concept in environmental issues (ecosystem services) into SDGs, although there is a problem in the lack of available data of some of these types of services.

We should not forget that the final purpose of the "indicators approach" is to aggregate all of them into a composite index, whose value quantifies the degree of sustainability of a certain system. Following Hák et al. (2016), the indicators' battery should be of a "*manageable size*", which still has not been determined, although some authors have suggested that 20 indicators might be an adequate number (Bell & Morse, 2003). In addition to the above comments, the use of an excessive number of indicators could be problematical, jeopardizing the necessarily operational character of the proposed SRP. In what follows, some of these reasons are given.

1. In order to establish the composite index, it seems appropriate to attach a preferential weight to each indicator. This weight aims to reflect the preference of an individual or group of stakeholders for one indicator with respect to another. To perform this task, a specific stakeholder has to answer questions on the relative importance of each indicator; this task is normally done following a "pairwise" comparison format (Saaty, 1977; Diaz-Balteiro et al., 2011). This strategy implies posing questions to the DM which, according to her/his level of rationality, means a number of questions equal to (n-1) or n(n-1)/2, n being the number of indicators considered. For a relatively high number of indicators, the elicitation of preferential weights might inevitably become a very thorny, if not impossible, task.
2. On the other hand, the practice of resorting to a large number of indicators could lead to redundant ones; that is, indicators that could be highly correlated with others and that, consequently, do not add any useful information to the problem analysed, but may complicate unnecessarily the different steps in the process undertaken. A well-known example, as indicated above, is the multitude of indicators defined under the SDG umbrella, many of which could be redundant ones (Ronzon & Sanjuán, 2020). Finally, for some authors, the composite indices based on redundant indicators serve more to provide an ideological bias rather than give new insights into the problem analysed (McGillivray, 1991).
3. In rigorous terms, sustainability is not an economic positive concept but a normative one (Schmieg et al., 2018), since it implies the current generation's concerns with the welfare of future ones. Despite this, it should not be forgotten that the final purpose of this type of work is to obtain reliable values for composite indices. Although subjective judgments, such as selecting a correct set of indicators, have to be made in order to construct a composite index (Cherchye et al., 2008; Zhou et al., 2012), it should be noted that this type of information could be the basis for supporting different economic and environmental policies. Hence, in one way or another, a social acceptance of the results obtained is necessary. Obviously, if some of the indicators represent judgment values related to personal value systems, it would be more difficult to achieve compromise consensuses accepted by society as a whole. Additionally, as other authors have reported, some indicators used in this analysis are not part of the sustainability concept, or their relationship with it is a very vague one (Ekardt, 2020), and, more important still, they do not respond to society's demands, but to private interests

(Diez-Cañamero et al., 2020). Thus, in the case studies reported in the literature, it is not surprising to find indicators on the lines of what nowadays are known as ethical production, corporate social responsibility, etc. These are highly laudable aspects, but their connection with the idea of a sustainable management of the environment (Hoque et al., 2018) is too frail. In short, although the sustainability concept has been accepted for several decades now as being an ethical principle (Wiersum, 1995), this does not imply accepting sustainability indicators focused on purely personal value systems. Finally, it would seem advisable to maintain this type of analysis, as far as possible, within the limits of positive economics, and away from what some authors define as arbitrary valuations associated with sustainability indicators (Zylicz, 2007).

4 A Necessary Linkage Between Circular Economy and Sustainability

The main aim of this paper was to make some reflections on how to provide sensible guidelines for setting up a sound, operational SRP in order to carry out a sustainable management of the environment. However, despite taking the risk of disconnecting the presentation from its leitmotiv, in this section some premises will be made that aim to establish links between the concept of circular economy and that of modern sustainability. This issue is crucial for a rational understanding and use of both concepts. It will be concluded that the important concept of circular economy is not an end in itself but an operational concept which, when correctly applied, could help to improve the level of sustainability of any economic system. In short, circular economy is a means and sustainability an end; as some authors point out, circular economy is a new approach to sustainability (Murray et al., 2017). Thus, examples of metrics used as indicators are usually found in circular economy strategies linked to SDG (Malik et al., 2015).

In fact, the finitude of the environment as a source of inputs and as a sink for waste established above makes the underlying linear model totally insufficient; in other words, it has been, refuted by empirical evidence. For this reason, around the end of the last century, as an alternative to the linear model, some environmental economists proposed a circular one as being a more realistic way to link the environment with economic systems (Pearce & Turner, 1991). In this circular perspective, obtaining a stable equilibrium between the environment and the economic system requires fulfilling the following necessary basic conditions:

- Regarding renewable resources: the rate of use (harvesting, capture, etc.) of the resource must be less than or equal to the rate of its biological regeneration.
- Regarding waste production: the amount of waste generated by production and consumption processes must be less than or equal to the assimilation capacity of the environment plus its industrial recycling capacity.
- Regarding non-renewable resources:

1. For those of an energetic character: the extraction rate must be less than or equal to the discovery rate plus the rate of substitution by any type of renewable energy.
2. With recycling services: the extraction rate must be less than or equal to the discovery rate plus the actual industrial recycling rate.

It is clear that, at any scale considered, an economic activity satisfying the above conditions can be undertaken in the long-term without reducing the current stocks of any component of the natural capital. In this direction, it is interesting to note that some authors have explained the relationship between circular economy and a strong sustainability orientation (D'Amato et al., 2017; Teigiserova et al., 2020). In short, following the path of circular economy is a good way to achieve the sustainability desired. Circular economy and sustainability can be considered to be like the positive and the negative of a photo, or the two sides of a coin (Stahel, 2019), although it would seem more efficient to consider that the former is the cause and the latter the effect. In short, circular economy can be regarded as being an efficient strategy for helping to achieve a sustainable management of the environment and its embedded resources. Finally, recent studies link sustainability issues with circular economy by using MCDM techniques (Mishra et al., 2019; Niero & Kalbar, 2019), especially by incorporating the idea of strong sustainability into MCDM models using composite indices (Garcia-Bernabeu et al., 2020). These ploys reinforce the interest in building a sound SRP for dealing not only with sustainable issues but also with the other side of the coin; i.e., the degree of circularity of a certain natural system.

5 Conclusions

Nowadays, the concept of sustainability requires an explicit recognition, not only of the finitude of the environment, but also of its multifunctional nature. That is, societies demand from the environment not only goods and services with market prices, but also several ecological functions with no market values, but that are essential to the welfare of modern societies. The "indicators approach" and its transfer to the MCDM field seems a fruitful way of adequately configuring a sensible conceptualization and measurement of the degree of sustainability of a natural system. This orientation, as has been commented on above, seems to be a promising manner to build up a theoretically sound and computationally efficient SRP. Important steps have been taken by researchers from different disciplines in this direction. Hopefully, these notes will clarify some of the topics and will help scientists and practitioners to improve the results obtained up to now, in order to obtain the desired SRP, which correctly addresses the current problems associated with the sustainable management of the environment and its embedded resources.

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Appendix

The Methodology of Scientific Research Programmes: An Outline

The methodology of Scientific Research Programmes (henceforth SRP) was proposed by Imre Lakatos in 1968 with the main purpose of overcoming some potential insufficiencies detected in the Popperian approach to the measurement of scientific knowledge progress. It was problematic for Lakatos to measure scientific growth by resorting to Popper’s approach, which is based on facing a hypothesis with observational statements for its corroboration or refutation. For Lakatos that confrontation should be made among more complex entities than a single hypothesis, or even an articulated set of hypotheses (i.e., a theory). In this direction, this author proposes an epistemic structure by the name of SRP. Potential scientific growth would be established by comparing successive series of SRP. An old SRP would be surpassed by a new one, when the new SRP presented a corroborated excess of empirical content with respect to the previous one. Popperian hypothesis testing remains valid for the corroboration or refutation of the so-called auxiliary hypotheses, which conform an essential part of the SRP as explained below.

In other words, an SRP is an epistemological structure, which provides a set of guidelines for the advance of the scientific knowledge in a certain field. Very briefly, the main elements forming the structure of an SRP are:

The Hard Core

The hard core is the basic component of an SRP. This element defines the nature and purpose of the programme. Normally, it represents a set of general hypotheses which form the basis from which the programme will be developed in the near future. The hard core is considered unfalsifiable in a Popperian sense, which implies introducing a conventional element in a specific SRP. In other words, the hard core becomes unfalsifiable due to a decision from its proponents.

The Protective Belt

The protective belt represents a set of auxiliary hypotheses introduced into the programme with the purpose of protecting the hard core from potential refutations. The auxiliary hypotheses are not ad hoc hypotheses, since they have to be tested independently by following the classic Popperian framework of conjectures and refutations.

The Negative Heuristic

This component of an SRP tells us what is not permitted during the development of the programme. Basically, any type of manoeuvre against the structure of the hard core, like implementing empirical testings to its basic hypotheses is forbidden.

The Positive Heuristic

This last component of an SRP represents a set of guidelines which indicate how a specific SRP can be developed and extended. For instance, the positive heuristic can indicate the recruitment of specific mathematical techniques, the design of particular experiments, etc. In short, these guidelines aim to increase the progressive nature of the programme.

For Lakatos, an SRP is progressive if it leads to advances and discoveries implying a significant growth of knowledge. On the contrary, an SRP degenerates if it stagnates throughout the time. In other words, the SRP degenerates if, for a certain period of time, it has not provided any significant advances and new discoveries. When this happens, the SRP will be confronted and substituted by a new, more progressive one. In short, for Lakatos, the growth in scientific knowledge is not achieved by changing hypotheses or theories for new ones, but by replacing an old SRP for a more progressive one.

The seminal works by Lakatos presenting in detail the SRP methodology can be found in: Lakatos (1968, 1970). A good pedagogical extension of the material presented in this Appendix can be seen in Chalmers (1982, chapter 7). In order to appreciate the potentiality of this type of methodology for addressing economic problems, the following two books of readings are recommendable: Latsis (1976), and Marchi and Blaug (1991).

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An ELECTRE-TRI Model for National Energy Sustainability Assessment

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Abstract Energy sustainability is nowadays a crucial part of modern economies that is depended on multiple complex factors. Governments worldwide over the last years have enhanced their efforts towards sustainable development. The energy policies however need to be constantly monitored due to the dynamic nature of the problem. Thus, the aim of this chapter is to propose a new methodology that can be used as a general framework for measuring the energy performance of countries. More specifically, it proposes the sorting of countries into four energy categories with the use of the ELECTRE-TRI method. The selection of the evaluation criteria is based on the framework of the Energy Trilemma Index, while a total of 119 countries are assessed based on the proposed approach. The main results indicated that the European countries have made significant improvements towards energy sustainability along with Australia, Japan, and the United States.

Keywords Energy sustainability · Multicriteria decision analysis · ELECTRE-TRI method · Energy Trilemma index

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1 Introduction

Over the last decades, the depletion of fossil fuels and the constant climate change, combined with an increase in energy demand have drawn the attention of governments worldwide (Ligus & Peternek, 2021). The dependance on mineral resources, that are continuously decreasing, cannot any longer be considered as viable solution, while the air pollution is causing environmental harm and health problems (IAEA et al., 2005). Specifically, the greenhouse gases (GHGs) that are emitted to the atmosphere are responsible for the global warming of the planet (Phillis et al., 2021). This mass effect, triggers the melting of icecaps, the destruction of ecosystems, the increased forest fires and land degradation and is the largest environmental problem of modern times (Grigoroudis et al., 2019).

In this context, the mitigation of environmental pollution and the adoption of alternatives ways for energy production is more urgent than ever (Cegan et al., 2017). However, modern economies are heavily depended on the energy sector making energy sustainability a complicated process that is affected by multiple factors. Besides the mineral resources dependency, various socioeconomic and technological factors are affecting sustainable development. For instance, social unevenness, economic recesses, and the COVID-19 pandemic are some of the obstacles that are negatively impacting the energy transition and the implementation of new energy policies (WEC, 2020).

Thus, the transition towards successful energy sustainability systems demands careful planning. Countries should aim in developing such policies that will allow them to preserve their socioeconomic growth and at the same time to invest in alternative energy resources (Çelikbilek & Tüysüz, 2016). Depending on only one energy source cannot be remunerative, due to the fact that each energy source has its own benefits and disadvantages. The Paris agreement in 2016 was a watershed towards climate change and energy sustainability in total. In particular, 196 countries were bounded to implement energy policies that will reduce the global temperature by 2 °C by 2030 (UNFCCC, 2016).

So far it is understood that the effective management and the adoption of strategies that would enhance the efforts of achieving energy sustainability shape a multiple factor problem and qualitative and quantitative indicators (socioeconomic, technological, environmental etc.) should be taken into consideration. Due to the significance of the problem, various frameworks have been proposed that aggregate several interrelated indicators into an overall composite index (Siksnelyte et al., 2018). A methodology that is capable to aggregate multiple indicators is MultiCriteria Decision Analysis (MCDA). The number of MCDA applications in the energy sector has been significantly increased during the last years, indicating the necessity of assessing sustainability, and also the appropriateness of MCDA methods to the problem (Greco et al., 2014).

The aim of this chapter is to assess and classify countries according to their energy performance. The selected indicators are based on the World Energy Trilemma Index, and include energy related criteria, as well as socioeconomic attributes. The aggregation of these indicators is based on the ELECTRE-TRI outranking method (Yu, 1992; Roy & Bouyssou, 1993; Figueira et al., 2010). The ELECTRE methods have been applied successfully to natural resources management problems (Govindan & Jepsen, 2016). The rest of the chapter is organized as follows. Section 2 includes a review of the application of ELECTRE methods to environmental problems, as well as a review of frameworks that have been developed regarding energy sustainability. The World Energy Trilemma Index is presented in Sect. 3 and the applied method ELECTRE-TRI is discussed in Sect. 4. The methodological framework of this study is introduced in Sect. 5, while Sect. 6 is devoted to the analytically presentation of the obtained results. Finally, Sect. 7 summarizes the concluding remarks of the study and potential future research opportunities.

2 Energy Sustainability Approaches

The energy sustainability is a broad area of study and has gathered the attention of many researchers. In this section, the application of ELECTRE methods in the energy sector will be presented, as well as other MCDA approaches in the same field. Moreover, some of the most recognized barometers regarding the energy sustainability of countries will be discussed.

2.1 Applications of ELECTRE Methods in the Energy Sector

ELECTRE methods have been applied in various sectors, particularly in problems related to waste management, natural resources management, geology, and forestry (Govindan & Jepsen, 2016). Furthermore, they have applied to problems regarding the evaluation of air quality, the mitigation of environmental harm, as well as the evaluation and selection of appropriate environmental indicators.

Regarding energy management, various implementations of the ELECTRE family of methods can be found in the literature. For example Karakosta et al. (2008) classified 16 different sustainable energy technologies for electricity generation according to the Clean Development Mechanism (CDM) using the ELECTRE-TRI method. In this study, six different environmental and socioeconomic criteria were used 16 alternatives were sorted into three priority categories.

Madlener et al. (2009) performed a comparative analysis, combing data envelopment analysis (DEA) and ELECTRE-TRI in order to assess 41 biogas industries in Austria. The industries were classified into four categories with the use of ELECTRE-TRI based on five environmental, economic, and social criteria.

In a different context, Oliveira et al. (2013) combined ELECTRE-TRI with evolutionary algorithms in order to focus the search base on the Decision Maker's preferences and also minimize the computational cost. The algorithms were examined on a combinatorial problem in electrical networks named EvABOR (Evolutionary Algorithm Based on an Outranking method).

Neves et al. (2018) introduced a methodology that would assist municipalities to develop an Energy Action Plan (EAP) and hence, become more energy sustainable. Sixteen actions were selected and evaluated with the use of the ELECTRE III method. The proposed framework was applied to the municipality of Odemira of Portugal.

Based on the aforementioned studies, it may observed that the ELECTRE family of methods has been applied to several studies regarding the energy sector. However, these studies are mainly focused on specific problems regarding the assessment of energy sustainability, while they do not refer to large-scale applications.

2.2 MCDA Approaches in Energy Sustainability

MCDA approaches have been extensively used in measuring energy sustainability and development. Siksnelyte et al. (2018) in an extended overview, examined 105 different published papers and found that AHP, TOPSIS and PROMETHEE methods are the most widely used MCDA techniques. However, there is a lack of studies regarding national energy performance evaluation.

Fu et al. (2021) assessed the energy efficiency of the top-ten best performing countries according to the energy trilemma index (ETI) 2018. They applied Principal Component Analysis (PCA) for measuring the significance of the three main ETI pillars: energy security, energy equity and environmental sustainability. In order to rank the countries, they used the fuzzy TOPSIS method.

In a similar context, Phillis et al. (2021) suggested a methodological framework for evaluating the energy performance of 43 countries. It is based on three main pillars: environment, human system and energy system and covers 24 indicators. The aggregation of the criteria was based on the PROMETHEE method.

Altintas et al. (2020) proposed a revised version of the grey rational analysis (GRA) integrated with fuzzy Analytic Hierarchy Process (AHP) in order to evaluate the energy performance of 35 OECD country member. The framework assessed an overall energy sustainability index (OESI) based on three main dimensions: economic and security, environmental and social.

A different energy performance evaluation of OECD countries was proposed by Pliousis et al. (2019). They implemented the "benefit-of the-doubt" (BoD) method, which is a variant of data envelopment analysis (DEA). Using data from 2005 to 2015 they ranked 34 OCED countries. Their framework was based on indicators provided by the energy trilemma index (ETI).

Cucchiella et al. (2017) assessed the sustainability performance of European countries with the use of the Analytic Hierarch Process (AHP) method. The evaluation criteria included both environmental (e.g., energy consumption, share of renewable energy in electricity) and energy sustainability indicators (e.g., government expenditures for environmental protection, recycled and reused wastes).

Guo et al. (2017) applied the DEA method to measure the environmental performance of 109 environmentally monitored cities in China. They used various pollutants as indicators and the results showed that most of the cities were focusing on economic growth rather than environmental protection, while there were significant differences among regions.

2.3 Other Barometers for Measuring Energy Sustainability

Over the last years, many researches have focused on developing indices that are able to measure and monitor the energy performance and development of counties. For example, the Environmental Performance Index ranks (EPI) evaluates 178 countries according to their ecological performance by combining 22 indicators (Neves Almeida & García-Sánchez, 2016). Similarly, ESI (Environmental Sustainability Index) measures the ability of countries to mitigate environmental harm incorporating 76 indicators of energy sustainability for 146 countries (Michalos, 2014). Furthermore, EVI (Environmental Vulnerability Index) quantifies the vulnerability of the natural environment to damage either from physical or human hazards for 224 countries (Kaly et al., 1999).

García-Álvarez et al. (2016) introduced an alternative ESI framework in order to evaluate 15 European Union (EU) countries by aggregating 33 indicators that represent 3 main dimensions:

- Energy supply safety (SES)
- Competitive energy market (CEM)
- Environmental Protection (EP)

Another recent index is RISE (Regulatory Indicators for Sustainable Energy), which assess 111 nations worldwide (Banerjee et al., 2017). It includes 27 criteria separated into 3 main pillars:

- Access to modern energy
- Energy efficiency
- Renewable energy

Its aim is to assist policymakers to address new strategies by providing comparison of national policies and regulatory frameworks.

Sachs et al. (2019) proposed the Sustainable Development Goals Index (SDGs) that measures a country's current performance based on 17 SDGs of the United Nations 2030 Agenda. In particular, based on the 17 SDGs, the authors set 169 detailed targets and means of implementation, were only 20 of them refer to sustainable energy, resilient cities, and climate action.

A different barometer is the Multidimensional Energy Poverty Index, (MEPI) (Nussbaumer et al., 2012), which estimates the access of nations to modern energy sources. MEPI is composed of five dimensions (cooking, lighting, services provided by means of household appliances, entertainment/education and communication that represent basic energy services).

Finally, Burck et al. (2020) proposed the Climate Change Performance Index (CCPI), which tracks 56 countries and the European Union's (EU's) progress towards the main Paris Agreement goal (reduction of global temperature by 2 °C). Specifically, CCPI assesses the countries' 2030 targets according to the weighted average of their scores against 14 energy indicators (e.g., emissions, renewable energy, and energy use).

3 ELECTRE-TRI Method

The ELECTRE-TRI method is a multicriteria outranking method that is used in sorting problems, i.e., the alternatives are assigned to predefined categories (Yu, 1992; Roy & Bouyssou, 1993; Figueira et al., 2010). Each alternative a is assessed separately from the others based on a set of criteria and it is classified into predefined classes. Let F denote the set of indices of the criteria $g_1, g_2, \ldots, g_m$ ($F = \{1, 2, \ldots, m\}$) and B the set of indices of the profiles that define $p + 1$ categories ($B = \{1, 2, \ldots, p\}$), where the profile b_h is the upper limit of category C_h and the lower limit of the category C_{h+1}, $h = 1, 2, \ldots, p$.

The assignment of the alternatives in the predefined categories is based on their comparison with these profiles (see Fig. 1) in order to validate or invalidate an outranking relation of the form aSb_h (or b_hSa) which indicates that "alternative a is at least as good as profile b_h.

The outranking relation is a two-stage process. Firstly, it involves the concordance test, which is used to evaluate the strength of the indications that support the outranking relation. This is achieved with the estimation of the concordance index $C(a, b_h)$ as follows:

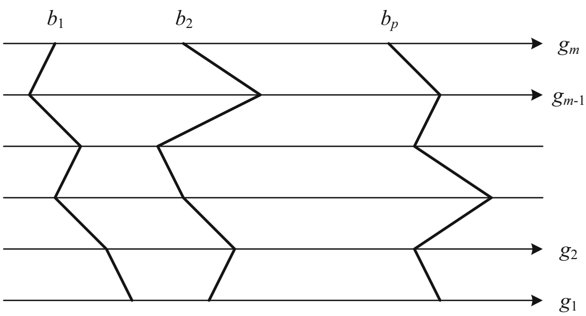

Fig. 1 Profiles and categories in ELECTRE-TRI

$$C(a, b_h) = \sum_{j=1}^{m} w_j c_j(a, b_h) \tag{1}$$

where $w_j \geq 0$ is the weight of criterion j (with $\sum_j w_j = 1$) and $c_j(a, b_h)$ is the partial concordance index for criterion j. The partial concordance index measures the strength of the outranking relation aS_jb_h which can be interpreted as "alternative a is at least as good as profile b_h on criterion j".

The partial concordance index is estimated as follows:

$$c_j(a,b_h) = \begin{cases} 0 & \text{if } g_j(a) \leq g_j(b_h) - p_j(b_j) \\ \dfrac{g_j(a) - g_j(b_h) + p_j(b_j)}{p_j(b_j) - q_i(b_j)} & \text{if } g_j(b_h) - p_j(b_j) \leq g_j(a) \leq g_j(b_h) - q_j(b_j) \\ 1 & \text{if } g_j(a) \geq g_j(b_h) - q_j(b_j) \end{cases} \tag{2}$$

where $p_j \geq q_j \geq 0$ are the preference and indifference thresholds for criterion j.

The second stage involves the discordance test, which assess the strength of the indications against the outranking relation. This is done with the estimation of the discordance index for each criterion j as follows:

$$d_j(a,b_h) = \begin{cases} 0 & \text{if } g_j(a) > g_j(b_h) - p_j(b_j) \\ \dfrac{g_j(b_h) - g_j(a) - p_j(b_j)}{v_j(b_j) - p_i(b_j)} & \text{if } g_j(b_h) - v_j(b_j) < g_j(a) \leq g_j(b_h) - p_j(b_j) \\ 1 & \text{if } g_j(b_h) - v_j(b_j) > g_j(a) \end{cases} \tag{3}$$

where $v_j \geq p_j$ is the veto threshold that represents the smallest difference $g_j(b_h) - g_j(a)$ incompatible with the assertion aSb_h.

The results from both stages are aggregated into the credibility index $\sigma(a, b_h)$, which is calculated as follows:

$$\sigma(a, b_h) = C(a, b_h) \prod_{j \in \overline{F}} \frac{1 - d_j(a, b_h)}{1 - C(a, b_h)} \tag{4}$$

where $\overline{F} = \{\, j \in F | d_j(a, b_h) > C(a, b_h)\}$.

The credibility index ranges in [0, 1] and indicates the overall degree of credibility of the outranking relation aSb_h. The outranking relation is considered valid if $\sigma(a, b_h) > \lambda$where λ is a user defined "cutting level" ranging in [0.5, 1] that determines the preference situation between a and b_h. In particular:

- $aIb_h \Leftrightarrow aSb_h$ and b_hSa, i.e., a is indifferent to b_h.
- $a \succ b_h \Leftrightarrow aSb_h$ and not b_hSa, i.e., a is preferred to b_h (weakly or strongly).
- $a \prec b_h \Leftrightarrow$ not aSb_h and b_hSa, i.e., b_h is preferred to a (weakly or strongly).
- $aRb_h \Leftrightarrow$ not aSb_h and not b_hSa, i.e., a is incomparable to b_h.

The outranking relation b_hSa is also checked with the same process. After the abovementioned analysis is complete, two assignment procedures are introduced: the pessimistic and the optimistic. In the pessimistic procedure each alternative is compared successively to the profiles b_i for $i = p, p - 1, \ldots, 0$. Let b_h be the first profile that the outranking relation aSb_h holds, and thus the alternative a is assigned to group C_{h+1}. In the optimistic procedure each alternative a is compared successively to the profiles b_i or $i = p, p - 1, \ldots, 0$. If b_h is the first profile such that $b_h \succ a$, then alternative a is assigned to group C_h.

The differences between of the two procedures arise in incomparability relations. For instance, in a two-group case scenario, an alternative that is incomparable to profile b_1 will be assigned to group C_1 in the optimistic procedure, while in the pessimistic scenario it will be placed to group C_2. Hence, the differences between the two procedures of assignment, allows the identification of alternatives with special characteristics, which rises the difficulty level of the comparisons of the alternatives.

4 World Energy Trilemma Index (ETI)

The World Energy Trilemma Index is published in a yearly basis from the World Energy Council (WEC) since 2010. The WEC provides a report that includes a ranking of 128 countries according to their energy performance and sustainability. The energy sustainability in accordance with WEC is based on three dimensions: energy security, environmental sustainability, and energy equity:

Energy security describes a nation's capacity to meet present and future energy demands, which reflects diversification of its energy supplies as well as the security of the supply that is related to the outer environment a country face. Moreover, it captures the extent of imports relative to a country's energy used, the reliability and resilience of energy infrastructures.

Energy equity evaluates the ability of a country to offer wide access to energy services for both domestic and commercial use. It includes the access to electricity along with the cost of the energy (e.g., electricity, gas, and diesel prices). This dimension indicates the economic growth of a country; an unequal disposable income distribution, along with high cost of the energy services restricts a citizen's well-being and purchasing power.

Finally, the environmental sustainability of energy systems encapsulates a country's regulations for mitigating the environmental harm in terms of the amount of produced energy, the substitution of energy sources (going from fossil fuels to renewable) and the air quality.

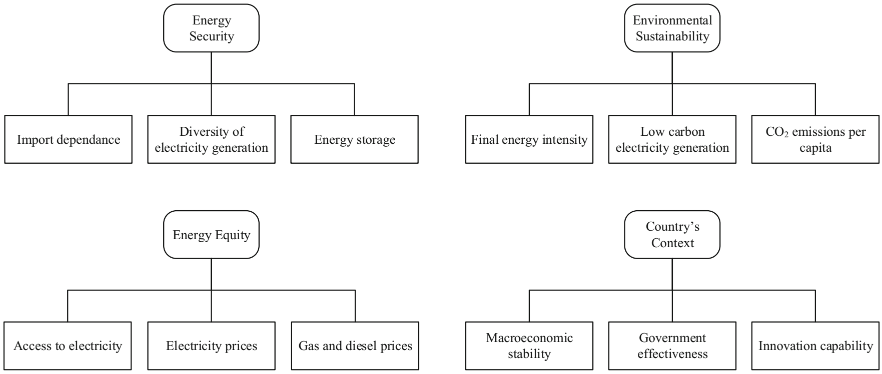

Fig. 2 Criteria of Energy Trilemma Index

ETI besides the three main energy and environmental dimensions, it integrates a socioeconomic dimension that describes a nation's ability to develop and apply energy policies. In specific, it includes the macroeconomic and government policies, the effectiveness of the government and a country's willingness to implement sustainable technologies.

The issued report of WEC, besides the ranking, grades each country with a rating system that ranges from A to D for each dimension. So, the total grade of a country has the following format: AAAa. Letter A marks the best performance in a particular dimension while D the worst. The lower-case letter is used to separate the socio-economic dimension from the others. Each dimension of ETI includes 3 indicators (12 in total). These indicators are used as the evaluation criteria on this study (Fig. 2).

Energy security includes:

- *Import dependance*: A country's dependance on net imports and the diversity of the suppliers that it uses
- *Diversity of electricity generation*: The different electricity sources that are being used for electricity production
- *Energy storage*: A country's ability to meet the demand for gas and diesel in accordance with its infrastructure capabilities.

The energy equity dimension includes:

- *Access to electricity*: The percentage of population that has access to electricity
- *Electricity prices*: National prices of electricity per kWh for both households and businesses
- *Gas and diesel prices*: Prices per liter as an indicator for affordable energy services for passenger and commercial vehicles

The environmental sustainability is defined by:

- *Final energy intensity*: Ration of total energy consumption over GDP
- *Low carbon electricity generation*: Percentage of electricity generation that is not produced from fusil fuels
- *CO_2 emissions per capita*: CO_2 emissions from fuel combustion per capita

Finally, the country's context dimension is defined by:

- *Macroeconomic stability*: Level of inflation and the sustainability of fiscal policy.
- *Government effectiveness*: Perceptions of the quality of public services and quality of policy formulation and implementation.
- *Innovation capability*: Capability of country to innovate including quantity and quality of formal R&D.

5 Methodological Framework

The aim of this chapter is to present an alternative approach for assessing a nation's energy performance by sorting the alternatives into predefined categories with the use of the ELECTRE TRI method. The categories should be able to successfully discriminate the countries that have achieved high energy performance compared to those that have worst performances.

In this study we propose the classification of countries into four energy performance categories:

- Excellent energy performance category (C_4)
- Good energy performance category (C_3)
- Sufficient energy performance category (C_2)
- Insufficient energy performance category (C_1)

The sorting procedure assesses the ability of countries to meet with some specific energy performance thresholds. This is important difference, in contrast to rating and ranking of countries. In particular, depending on what energy and environmental policies a country applies it will be sorted properly into the abovementioned categories.

Regarding the assessment of energy sustainability, the World Energy Council indicators were adopted with small modifications. Thus, the number of criteria is 14 in total, where the 11 refer to the energy and environmental dimensions and the rest are socioeconomic ones:

- Criterion g_1: Import dependance
- Criterion g_2: Diversity of electricity generation
- Criterion g_3: Energy storage
- Criterion g_4: Access to electricity
- Criterion g_5: Electricity prices for households
- Criterion g_6: Electricity prices for businesses
- Criterion g_7: Diesel prices

Table 1 Measurement units for the evaluation criteria

Criteria (g_i)	Measurement units
Import dependance	% Of energy use
Diversity of electricity generation	Simpson's Diversity index in [0, 1]
Energy Storage	% of GNI (Gross National Income)
Access to electricity	% of total of population
Electricity prices for households	$USD per kWh
Electricity prices for businesses	$USD per kWh
Gasoline prices	$USD per liter
Diesel prices	$USD per liter
Final Energy Intensity	MJ/$2011 PPP GDP
Low carbon electricity generation	% of renewable resources
CO_2 emissions per capita	Metric tons per capita
Macroeconomic Stability	Values in [0, 100] (Global Competitiveness Index)
Effectiveness of Government	Values in [−2.5, 2.5] (World Governance Indicators)
Innovation Capability	Values in [0,100] (Global Competitiveness Index)

- Criterion g_8: Gas prices
- Criterion g_9: Final energy intensity
- Criterion g_{10}: Low carbon electricity generation
- Criterion g_{11}: CO_2 emissions per capita
- Criterion g_{12}: Macroeconomic stability
- Criterion g_{13}: Government effectiveness
- Criterion g_{14}: Innovation capability

The differences compared to ETI are related to the prices of electricity, where two different criteria were used for households and businesses. Similarly two separate criteria were created for gas and diesel prices for more accurate evaluation process. Table 1 summarizes the indicators along with the measurement units.

In order to apply the ELECTRE-TRI method, the following parameters should be determined:

- Profiles (b_h)
- Preference threshold (p_i)
- Indifference threshold (q_i)
- Veto threshold (v)
- Weights of the criteria (w_i)

The profiles b_h separate the predefined categories from the highest to the lowest. Since four categories have been set, three profiles must be defined. In particular profile b_1 express the minimum values in the set of criteria that a country should meet in order to be classified into the poorest energy performance category (C_1). Profile b_2 refers to the values of the criteria that a country should have in order to be classified into the sufficient performance category (C_2). Similarly, profile b_3 separates the good energy performance category (C_3) from the category of excellent performance (C_4).

Table 2 Profiles

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}	g_{13}	g_{14}
b_1	0.45	0.35	2	70	0.17	0.17	1.2	1.30	6.0	0.50	7.0	60	0.0	40
$b2$	0.75	0.45	4	85	0.11	0.11	0.9	0.95	5.0	0.65	5.5	75	0.7	50
b_3	0.95	0.6	6	98	0.08	0.1	0.7	0.80	4.5	0.80	4.0	85	1.5	60

Table 3 Preference, indifference, veto thresholds and criteria weights

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}	g_{13}	g_{14}
w	0.1	0.1	0.1	0.1	0.05	0.05	0.04	0.04	0.1	0.1	0.1	0.06	0.05	0.05
q	0.1	0.1	1	4	0.03	0.02	0.1	0.1	0.2	0.5	0.5	4	0.1	2
p	0.3	0.2	1.2	4	0.3	0.02	0.12	0.12	0.6	0.8	0.6	5	0.12	2.5
v	5	–	–	35	–	–	–	–	–	0.5	–	30	–	–

The weights of the criteria were adjusted in accordance with the importance of the WEC indicators. For instance, none of the socioeconomic criteria received higher weight than the environmental.

In order to define the parameters of the problem, multiple tests were performed in the set of alternatives in order to reduce the misclassification errors with the use of the ELECTRE-TRI software. The obtained results were similar to the results of ETI, e.g., no country that ranked among the top performers of ETI was sorted in the lowest performing category. Thus, the results of the study can be used for drawing reliable conclusions. The proposed methodology offers great flexibility, as the parameters may adjusted according to the preferences of each decision maker, or in this kind of problems, according to the energy performance results that policymakers want to achieve. The values of the three profiles are presented in Table 2, while the parameters of the ELECTRE-TRI method are shown in Table 3.

Profiles b_1 and b_2 have relatively small differences in their values compared to profile b_3. This adjustment allows for a country that adopts new effective energy policies to be sorted properly into the right category and encourage to plan new strategies, while for a country to be considered as an excellent performer (to be considered better than profile b_3) it must have a remarkable energy strategy and successfully meet specific regulations.

Figure 3 summarizes the applied methodological framework.

6 Results and Discussion

The pessimistic and optimistic classification of the countries are presented in Table 4. In total 119 countries were included in this research, and only 16 were incomparable with one profile. As already mentioned, these deviations refer to only on category. For instance, Australia is classified in the pessimistic procedure in the third category (C_3), while in the optimistic in the fourth category (C_4). Thus,

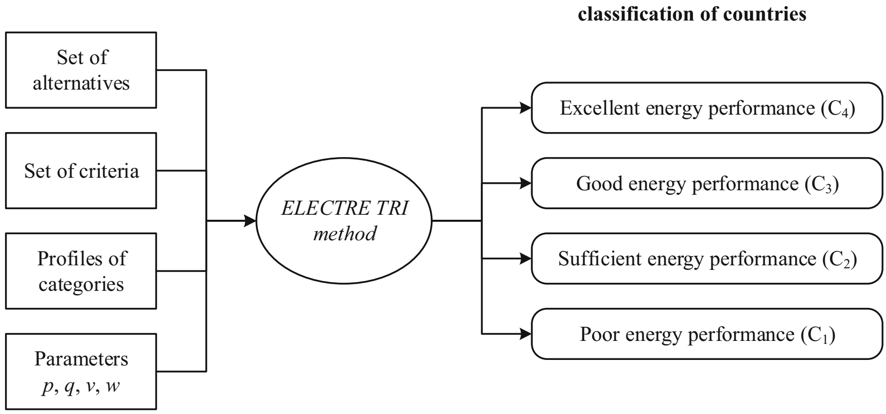

Fig. 3 Methodological framework for the classification of countries

incomparability is related only to profile b_3 and does not involve other profiles that would made the interpretation of the results more complex. Generally, it is up to the decision maker to decide the final sorting of countries, according to the characteristics that believes better describe the energy performance of a country. Most of the countries were classified as sufficient energy performers, while only a small number of countries are assigned in the fourth group.

Examining the abovementioned results per region may not only reveal interesting finding, but can also help in validating the estimated classification of countries. Specifically, most of the European countries have been sorted in the excellent performance category (C_4) as it can be observed Fig. 4. It is notable that only one European country falls into the category of poor energy performance. These results indicate that the European countries have shifted towards energy sustainability over the last years and are implementing successful energy policies.

On the other hand, most of the African countries are classified as insufficient energy performers. Despite the fact, that the dataset does not include all the countries of the African continent, the included countries form a representative group that has major differences to the European countries with respect to energy sustainability. In fact, only 6 countries out of 22 were sorted in the sufficient energy performance category C_2 and the rest are included into the last group (C_1) (Fig. 5). The different climate conditions, the various topographies, and other factors of the African countries, may partially justify their underperformance, but at the same time highlights the necessity of a united effort that would lead to better energy performances.

Asian countries form a special region, as most of them are divided between the first (C_1) and the third (C_3) category, while only one is included in the second category (Fig. 6). These results show that there are countries that have adopted and apply new energy policies, while other countries perform poorly and need to reassess their policies.

Figure 7 shows the classification of Middle East countries. Notwithstanding that they border with the Asian countries and geographically face similar issues, their

Table 4 Classification of countries with ELECTRE-TRI

Country	Pessimistic classification	Optimistic classification
Australia	C_3	C_4
Austria	C_4	C_4
Canada	C_4	C_4
Colombia	C_4	C_4
Costa Rica	C_4	C_4
Czech Republic	C_4	C_4
Denmark	C_4	C_4
Estonia	C_3	C_4
Finland	C_4	C_4
France	C_4	C_4
Germany	C_4	C_4
Hungary	C_4	C_4
Iceland	C_4	C_4
Italy	C_4	C_4
Japan	C_4	C_4
Latvia	C_3	C_4
Luxembourg	C_4	C_4
Malaysia	C_4	C_4
Netherlands	C_4	C_4
New Zealand	C_4	C_4
Norway	C_4	C_4
Portugal	C_4	C_4
Saudi Arabia	C_4	C_4
Slovenia	C_4	C_4
Spain	C_4	C_4
Sweden	C_4	C_4
Switzerland	C_4	C_4
United Arab Emirates	C_4	C_4
Uruguay	C_4	C_4
USA	C_4	C_4
Profile b_3		
Argentina	C_3	C_3
Armenia	C_3	C_3
Azerbaijan	C_3	C_3
Belgium	C_3	C_3
Brazil	C_3	C_3
China	C_3	C_3
Ecuador	C_3	C_3
United Kingdom	C_3	C_3
Georgia	C_3	C_3
Croatia	C_3	C_3
Hong Kong	C_3	C_3

(continued)

Table 4 (continued)

Country	Pessimistic classification	Optimistic classification
Indonesia	C_3	C_3
Ireland	C_3	C_3
Iran	C_3	C_3
Israel	C_3	C_3
Kazakhstan	C_3	C_3
Kuwait	C_3	C_3
Lithuania	C_3	C_3
Mexico	C_3	C_3
North Macedonia	C_3	C_3
Panama	C_3	C_3
Peru	C_3	C_3
Paraguay	C_3	C_3
Qatar	C_3	C_4
Romania	C_3	C_3
Russia	C_3	C_3
Singapore	C_3	C_3
Slovak Republic	C_3	C_3
Paraguay	C_3	C_3
Romania	C_3	C_3
Russia	C_3	C_3
Singapore	C_3	C_3
Profile b_2		
Albania	C_2	C_2
Bulgaria	C_2	C_2
Bosnia and Herzegovina	C_2	C_2
Bolivia	C_2	C_2
Botswana	C_2	C_2
Chile	C_2	C_3
Cyprus	C_2	C_2
Dominican Republic	C_2	C_2
Algeria	C_2	C_2
Greece	C_2	C_2
Guatemala	C_2	C_3
Iraq	C_2	C_2
Korea	C_2	C_3
Morocco	C_2	C_2
Malta	C_2	C_3
Montenegro	C_2	C_2
Mauritius	C_2	C_3
Namibia	C_2	C_2
Oman	C_2	C_3
Philippines	C_2	C_3

(continued)

Table 4 (continued)

Country	Pessimistic classification	Optimistic classification
Poland	C_2	C_2
Serbia	C_2	C_2
South_Africa	C_2	C_2
Thailand	C_2	C_2
Tunisia	C_2	C_2
Turkey	C_2	C_2
Ukraine	C_2	C_3
Vietnam	C_2	C_2
Profile b_1		
Angola	C_1	C_1
Benin	C_1	C_1
Bangladesh	C_1	C_1
Bahrain	C_1	C_1
Cameroon	C_1	C_1
Congo	C_1	C_1
El Salvador	C_1	C_1
Egypt, Arab Rep.	C_1	C_1
Ethiopia	C_1	C_1
Gabon	C_1	C_1
Ghana	C_1	C_1
Honduras	C_1	C_1
Jamaica	C_1	C_1
Jordan	C_1	C_1
Kenya	C_1	C_1
Cambodia	C_1	C_1
Sri Lanka	C_1	C_1
Moldova	C_1	C_1
Madagascar	C_1	C_1
Mongolia	C_1	C_1
Mozambique	C_1	C_1
Nigeria	C_1	C_1
Nicaragua	C_1	C_1
Nepal	C_1	C_1
Pakistan	C_1	C_1
Senegal	C_1	C_1
Tajikistan	C_1	C_1
Trinidad and Tobago	C_1	C_1
Tanzania	C_1	C_1
Zambia	C_1	C_1
Zimbabwe	C_1	C_1

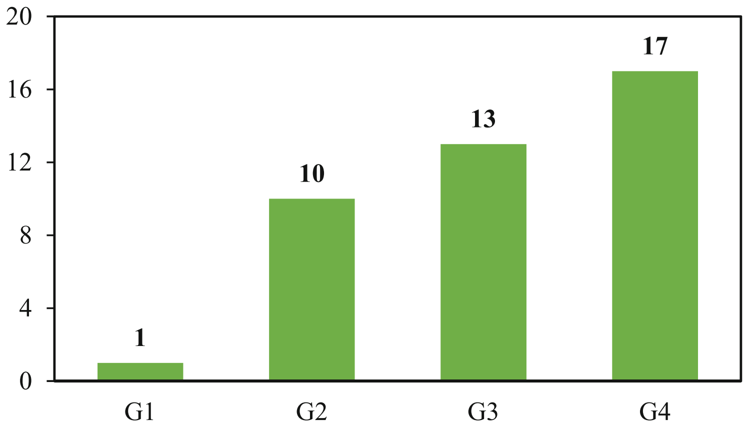

Fig. 4 Classification of European countries

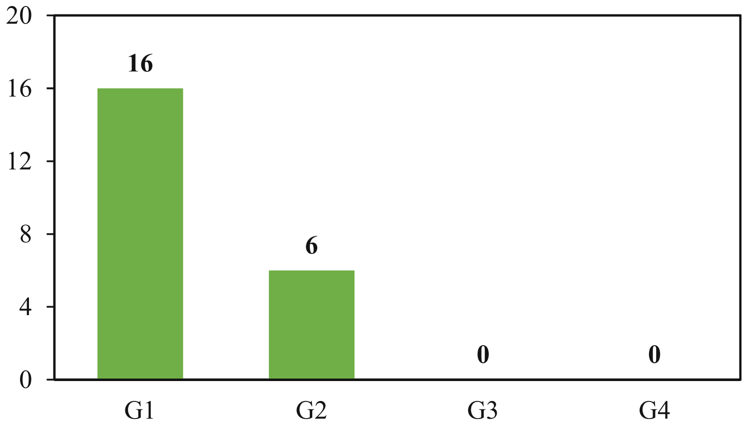

Fig. 5 Classification of African countries

respective classification is quite different (Fig. 7). In particular, one may argue that each Middle East country face different energy issues, apply different energy policies, or even have a different commitment towards energy sustainability.

Finally, Latin American countries are almost evenly classified into the four categories, indicating that it is a diverse regional group. Nonetheless further effort is required for an adequate regulatory framework. The top performing countries (C_4) are Colombia, Costa Rica, and Uruguay (Fig. 8).

These results are consistent with several studies that emphasize a strong relation between income (wealth) and sustainability performance (see for example Grigoroudis et al., 2021).

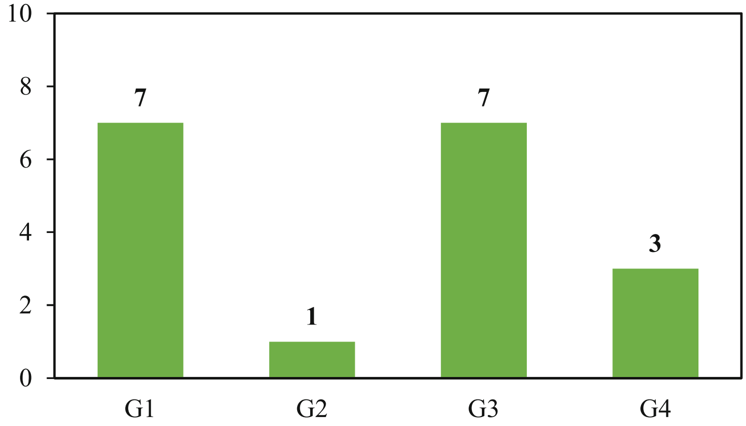

Fig. 6 Classification of Asian countries

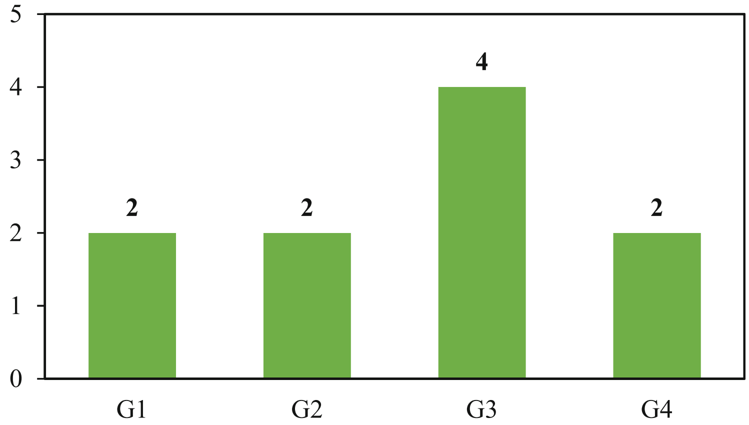

Fig. 7 Classification of Middle East countries

7 Conclusions and Future Research

Climate change has alerted countries all over the world, and in the last years they have focused their attentions in reassessing and adopting new energy regulations. Under this context, many researchers have developed indices for monitoring the progress of countries in terms of energy sustainability. The aim of this study is to introduce a new alternative approach to the topic. The applied method (ELECTRE-TRI) has not been used in this context and offers several advantages. Firstly, it differentiates from most of the other methods that provide country rankings, as it classifies them into predefined sorted categories. The proposed classification of countries into four ordered groups according to their energy performance is

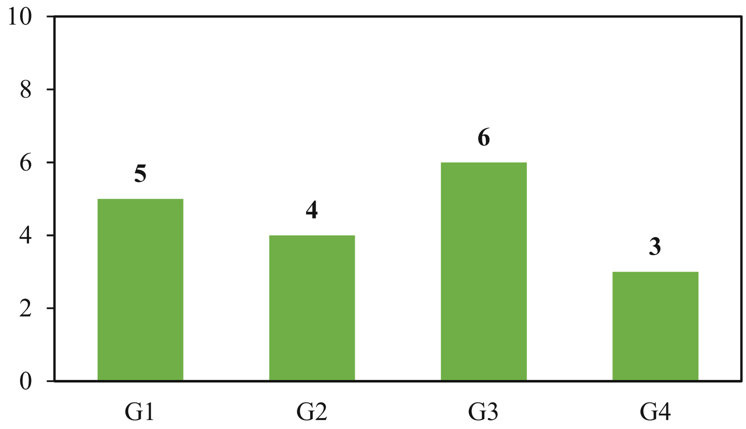

Fig. 8 Classification of Latin American countries

consistent with the framework of the Energy Trilemma Index. Similarly, the evaluation criteria are also based on the indicators of the Energy Trilemma Index.

The obtained results show that the best performers are in majority European countries, while on the other hand African countries should readjust their energy policies. In total 119 countries are evaluated.

One of the most important advantage of the proposed methodology is the profiles that discriminate the four categories. They offer great flexibility as their values are able to be adjusted according to the regulations and policies that a country needs to implement. If the values of the profiles remain the same in a certain period of time the countries can monitor their progress. However sustainable development can be affected by various environmental, political, economic, or socioeconomic reasons. For instance, the COVID-19 pandemic is expected to alter the energy transition policies, so the profiles can be customized accordingly and produce up-to-date results.

Future research efforts may compare the ELECTRE-TRI results with other well-established frameworks. This would allow to track down possible weaknesses and strengths. Moreover, an infusion of a MCDA method that also produce the ranking of the countries could offer more information of their energy performance. Finally, the extension of the sorting framework should be broadened to include more countries.

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Towards Sustainable Development and Climate Co-governance: A Multicriteria Stakeholders' Perspective

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Abstract Although 2015 featured the adoption of the 2030 Agenda for Sustainable Development, broken down into 17 sustainable development goals (SDGs), the year is mostly remembered for the global climate targets of the Paris Agreement. Seemingly two separate agendas, sustainable development and climate action are highly intertwined: the former is an explicit part of the Paris Agreement, while the latter constitutes one of the 17 goals. And they both emphasise the need to consider the interests and views of the broad societal range in the decision-making process, in an inclusive dialogue. This study uses a multi-criteria group decision analysis framework, based on the TOPSIS method and the 2-tuple linguistic representation model, to capture European climate stakeholders' perceptions of the urgency to integrate other SDGs in scientific support of climate policy design that is based on climate- and energy-economy modelling. We find that stakeholders prioritise sustainability aspects related to biodiversity and ecosystems as well as responsible resource use and social equalities, as targets to integrate in modelling exercises for climate change and policy. Based on a novel consensus measuring approach, we also find high consensus overall, with national policymakers however displaying assessments concentrated in the lower end of the importance scale.

Keywords Sustainable development goals · Multi-criteria decision aid · Climate co-governance · Climate policy · TOPSIS · 2-tuples

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1 Introduction

In 2000, the UN held the Millennium Summit to encourage world leaders to commit to fulfilling a set of eight targets known as the Millennium Development Goals (MDGs) until 2015 (UN, 2000). These targets placed significant weight on alleviating extreme poverty in multiple dimensions that include environmental sustainability (Sachs & McArthur, 2005) and were generally considered an important step to monitoring socio-economic growth especially for developing countries (Easterly, 2009), while also engaging NGOs and citizens (Brinkerhoff et al., 2007) in the process. The observed progress towards the targets (Sachs, 2012) led world leaders to extend the MDGs for the next 15-year period (Griggs et al., 2013) by enhancing the targets until 2030, paving the way for the adoption of the Sustainable Development Goals (SDGs) in 2015, in parallel with the Paris Agreement. As part of the Agenda for Sustainable Development, the SDGs constituted a set of 17 interconnected goals (Nilsson et al., 2016) with a broad range of targets that represent multiple sustainability dimensions, including land and water life preservation, clean energy, and socio-political goals. Climate action (SDG 13) has been found to have strong interlinkages with other SDGs (Köberle et al., 2020), showcasing that SDGs and the Paris Agreement are inseparable, since the pathway towards a "well-below" 2 °C affects, and is affected by, different SDG targets (Nerini et al., 2018).

Despite the undoubted value of SDGs in studying pathways and roadmaps to sustainability (Fuss et al., 2016; Roe et al., 2019), policymakers at the country level are still hesitant on their efforts to pursue these goals due to lack of clear understanding on how to translate the global targets in their national and local contexts (Bryan et al., 2019). On the other hand, it has been found that SDGs can be adequately assessed with climate policy assessment tools (Grubler et al., 2018), including integrated assessment models (IAMs) or climate-economy and energy systems models (Nikas et al., 2019). The representation of SDGs in IAMs was thoroughly examined by van Soest et al. (2019), who argued that most goals are only partially represented through some of their sub-goals/indicators. This is because these sub-goals are not always useful or meaningful in terms of mitigation analysis and fall outside modelling capabilities. For example, Fujimori et al. (2019) highlight the importance of combating climate change (SDG 13) in connection with SDG 2 due to trade-offs between climate change mitigation and food security, via the "people at risk of hunger" metric, i.e. a subset of the broader "food security" notion. Similarly, Iyer et al. (2018) limited the analysis on certain SDG subsets to study the impacts of nationally determined contributions (NDCs) on SDGs using the GCAM model, using air quality, energy access, energy security, food security, and ocean health as proxies for measuring SDGs 3, 7, 2 and 14 respectively. On the other hand, Luderer et al. (2019) represented air quality using a more diverse set of metrics, including particular matter formation and ionising radiation, which is relevant in scenarios with increased nuclear power. McCollum et al. (2018b) in a model intercomparison exercise studied SDGs 2, 3, 4, 6, 7 in line with the Paris Agreement goals. Table 1 presents recent modelling studies that discuss SDG implications from climate change mitigation policies.

Although these state-of-the-art studies provide valuable insights in terms of achieving SDGs, the fact that results are heavily influenced by parameter choices made by modelling teams or forced due to limitations in model capabilities may lead to reluctance or hesitation to make use of the resulting policy prescriptions. This adds to an existing criticism of IAMs that they are complex and often regarded as black boxes (Doukas et al., 2018), making it difficult for stakeholders to translate their outcomes into action or even engage in the scientific process in the first place. However, this strong interdependence of SDGs with energy and the various and complex interactions among them creates the necessity to establish new approaches in integrated assessment policy efforts (McCollum et al., 2018a). To bridge this gap, much like other complex problem domains (Zopounidis & Doumpos, 2002), multi-criteria decision analysis (MCDA) is often used to assist decision makers in the challenging task of climate policymaking (Doukas & Nikas, 2020). Combined with climate- and energy-economic models, MCDA is usually implemented to optimise the modelling outputs and create robust policy mixes (Shmelev & Van Den Bergh, 2016), evaluate alternatives (Baležentis & Streimikiene, 2017) or rank associated transitional risks (Jun et al., 2013; Nikas et al., 2020b). However, MCDA can also be used to provide input to models through the inclusion of stakeholders and their preferences. Such mixed methodologies are found to perform better in terms of dealing with complexities in decision making than solemnly relying on IAMs (Scholten et al., 2017). This shifts the discussion on the climate change and action framing in the broad sustainability spectrum from what IAMs alone can provide (Nikas et al., 2021), to what stakeholders believe is important to study and which assumptions are more impactful.

In the context of expanding modelling capabilities to incorporate stakeholder preferences, this study uses the 2-tuple TOPSIS model, an MCDA technique, to prioritise the SDGs. The selected framework draws from a systematic literature review on MCDA studies that examined SDGs, in different approaches, with special focus on climate policy. In a group decision making framework based on a regional stakeholder workshop for the PARIS REINFORCE research and innovation project, we reach a ranking of SDGs ranking expressing the preference of the participating 31 stakeholders in terms of the need to incorporate SDGs in modelling exercises and extract SDG-relevant indicators from climate-economy modelling simulations. An important point this study also attempts to capture is the fluctuations in preferences between the different stakeholder groups. Towards identifying these trends and increasing robustness of the outputs, the analysis is also coupled with consensus measuring techniques.

Table 1 Recent modelling studies that discuss implications on SDGs from mitigation policies

Study	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
Luderer et al. (2019)			√			√						√		√	√		
von Stechow et al. (2016)		√	√				√	√	√			√	√	√			
Fujimori et al. (2019)		√											√				
Doelman et al. (2020)		√											√				
Vandyck et al. (2018)		√	√				√						√		√		
Gil and Bernardo (2020)							√	√					√				
van der Zwaan et al. (2018)	√						√	√					√				
van Soest et al. (2019)	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Rosenzweig et al. (2017)		√	√														
Parkinson et al. (2019)						√							√				
Ribas et al. (2017)							√										
Ribas et al. (2019)	√	√	√	√	√	√	√	√		√							
McCollum et al. (2018a)	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Roe et al. (2019)		√				√						√		√	√		

Dooley et al. (2018)		√											√		√		
Zhou et al. (2020)		√	√			√	√										
Michaelis and Wirths (2020)														√	√		
Dalla Longa and van der Zwaan (2017)							√				√		√				
McCollum et al. (2018b)		√	√	√		√	√						√				
Taliotis et al. (2020)							√						√				
Wachsmuth et al. (2019)			√														
Fuhrman et al. (2019)			√							√							
Lucas et al. (2019)		√	√	√		√	√						√				
Byers et al. (2018)	√	√				√	√						√		√		
Jakob et al. (2019)		√	√	√													
Godinez et al. (2020)		√												√	√		
Liu et al. (2019)		√	√				√						√		√		
Iyer et al. (2018)		√	√				√							√			
van der Zwaan and Dalla Longa (2019)							√						√				

(continued)

Table 1 (continued)

Study	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
van de Ven et al. (2019)			√				√						√				
Johnson et al. (2019)						√											
Portugal-Pereira et al. (2018)			√								√						
Humpenöder et al. (2018)		√					√						√	√	√		
Doelman et al. (2019)		√											√				
Garcia-Casals et al. (2019)								√									
Fujimori et al. (2020)		√	√			√	√	√	√			√			√		
Capellán-Pérez et al. (2020)							√										
Rafaj et al. (2018)			√				√				√		√				
Gil et al. (2019)	√	√											√	√	√		
Fuss et al. (2016)	√	√					√							√	√		
Haga et al. (2020)							√						√		√		
Tatarewicz et al. (2019)							√						√				
Kearney (2019)													√				

Dioha and Kumar (2020)										√							
O'Neill et al. (2020)				√													
Lanati et al. (2019)							√										
Dagnachew et al. (2018)							√										

2 The Use of MCDA in SDG Analysis

MCDA is a dominant field of operational research, with a wide range of applications. In relation to climate change, MCDA techniques have been found to be successfully employed to support decision makers in sustainability and climate policy problems (Doukas & Nikas, 2020). In this section we examine the extent to which MCDA has recently been used in the literature to assess SDGs and map the different roles SDGs play in the analysis. To investigate this, a thorough literature review was conducted to identify relevant scientific publications since 2016 by using the following two queries in Google Scholar:

- "multiple-criteria decision" + SDGs + "sustainable development goals"
- "multi-criteria decision" + SDGs + "sustainable development goals"

This search resulted in a vast literature review comprising 164 peer-reviewed articles in scientific journals related to the implementation of MCDA models for the analysis of SDGs. A first filtering can be conducted according to the method of MCDA used (Fig. 1). It is important to note that several studies used more than one MCDA methods, as well as that Fig. 1 presents only the methods employed in more than one study. Some studies furthermore used a method that they developed, without naming it (e.g. Choi et al., 2020), or failed to name the method used (e.g. Wu et al., 2020).

Figure 1 indicates that AHP is the dominant method, due to its versatility to be used standalone or in combination with other frameworks, then followed by TOPSIS. For example, Phonphoton and Pharino (2019) examined alternative

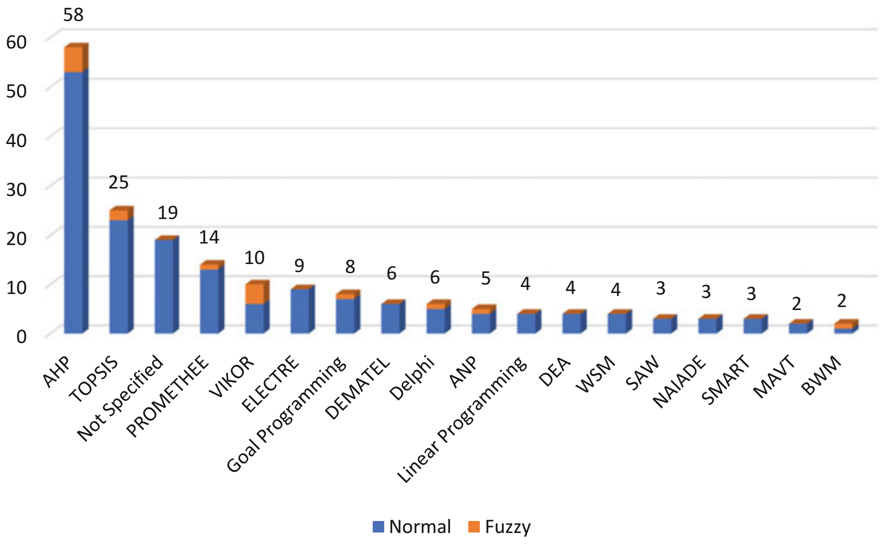


Fig. 1 The number of papers using each MCDA method

solutions for the waste management system of Bangkok, Thailand, focusing on criteria like food security (SDG 2), human health (SDG 3), water resources (SDG 6) and impact on biodiversity (SDG 15). Ullah et al. (2018) investigated the impact of three alternative gaseous fuel types on the transportation sector of Pakistan, using SDG-based criteria tracing to human well-being (SDG 3), economic growth (SDG 8) and climate action (SDG 13). Coupled with other methods, AHP is frequently applied to calculate the criteria weights in sustainability problems (Neofytou et al., 2020), before feeding the results to other frameworks performing the final evaluation of the alternatives. An interesting example is Guzman-Sanchez et al. (2018), who used AHP with TOPSIS, to assess the impact of various roof types on the sustainability of the building sector through AHP-weighed indicators that are directly linked to sub-goals of various SDGs (1, 2, 3, 6, 7, 8, 11, 12, 13, 14, and 15).

Another important insight from Fig. 1 is that several studies used fuzzy MCDA methods. For example, 40% of the VIKOR studies use the fuzzy version of the method, such as Hameed et al. (2020) that used fuzzy VIKOR to examine the impact of several risks related to e-waste and, linking risks to SDGs as criteria, concluded that pollution from e-waste recycling is one of the major risks, linked to SDG 13. Fuzzy methodologies are found to be relevant in handling uncertainty (Linkov et al., 2006), which is a key aspect of exercises that include stakeholders. However, MCDA methods can also be applied in stakeholder engagement processes without necessarily using fuzzy versions (Huang et al., 2011). Table 2 summarises the key studies that include stakeholder engagement as part of the MCDA framework for SDGs-related analysis. Although numerous studies include experts in the analysis, we highlight those mobilising the knowledge embedded in a noteworthy number of participants while presenting a diversity in means of engagement, regions, and focus areas.

Apart from reviewing the MCDA methods used for SDG analysis, it is important to investigate the roles SDGs played in each study. Three categories are identified based on how SDGs are assessed:

1. Criteria (SDGs are either directly used as criteria or indirectly through sub-goals)
2. Focus areas (SDGs provide the scope, context and/or research questions of the studies)
3. Alternatives (SDGs constitute, or are related with the selected alternative options)

Expectedly, the first of these categories is the most common as progress in sustainability dimensions, explicitly referred to via SDGs or implicitly tracing back to SDGs, provide a useful evaluation for alternative strategies, technologies, policies, etc. (Fig. 2).

Figure 2 showcases that the SDGs most referred to as criteria on MCDA methods are climate action (SDG 13), good health and well-being (SDG 3), decent work and growth (SDG 8), clean water (SDG 6), and affordable and clean energy (SDG 7). In most of these studies, SDGs are implicitly used to define related criteria, highlighting a tendency of the sustainability literature to focus on indicators like emission reduction, health and economic impacts, and access to clean energy and water, to assess the different alternatives. For example, Diemuodeke et al. (2019) used

Table 2 MCDA studies on or around SDGs including stakeholder engagement

Study	Method	Means of engagement	Region	Focus area
Ahmed et al. (2020b)	Delphi, AHP, fuzzy VIKOR	Electronic questionnaires to 12 industrialists, zone planners, environmentalists, and government officials	Pakistan	Selection of sustainable and special economic zones
Balali and Valipour (2020)	AHP	Interviews and questionnaires with 144 experts in Shiraz (Iran) buildings	Iran	Identify and prioritise the most suitable building facade's smart materials according to SDGs
D'agata et al. (2020)	TOPSIS	666 surveys with fisher households and 89 communities' key informants	Madagascar, Kenya	Social adaptive capacity of fishing households
Deshpande et al., (2020)	MAVT	31 responses in a scientific workshop	Norway	Assessment of environmental, economic, and social impacts of landfilling, incinerating, and recycling of waste fishing gears
Hameed et al. (2020)	Fuzzy VIKOR	150 surveys with engineers, industrial experts and academics on chemical and material engineering	Pakistan	Evaluation of environmental risks using modified-SIRA
Jamal et al. (2020)	AHP	Survey with 71 academics, industry experts and consultants	Australia	Microgrid planning and off-grid power supply system options for a remote rural area
Zeug et al. (2019)	Mean averages	64 stakeholders (society, business and science stakeholder groups)	Germany	Relevance of SDGs to bioeconomy
Lehner et al. (2018)	AHP	83 remote sensing experts' judgements from online questionnaires	Global	Indicators for sustainable city development through remote sensing data, in the context of the International Standard ISO 37120

TOPSIS to evaluate various alternatives for hybrid energy systems in Nigeria based on CO_2 emissions and renewable energy share, both constituting SDG sub-indicators (13.2.2 and 7.2.1, respectively).

In relation to climate change mitigation, over 100 of the examined studies used SDG 13 as an explicit or implicit criterion in their analysis or focus on its achievement. Table 3 presents some of these studies that find application in a broad range of sustainability areas and regions. On the other hand, since most MCDA studies focus on the selection of technological or policy alternatives, societal issues like inequalities and peace are rarely examined. In particular, SDGs 5 (Gender Equality),

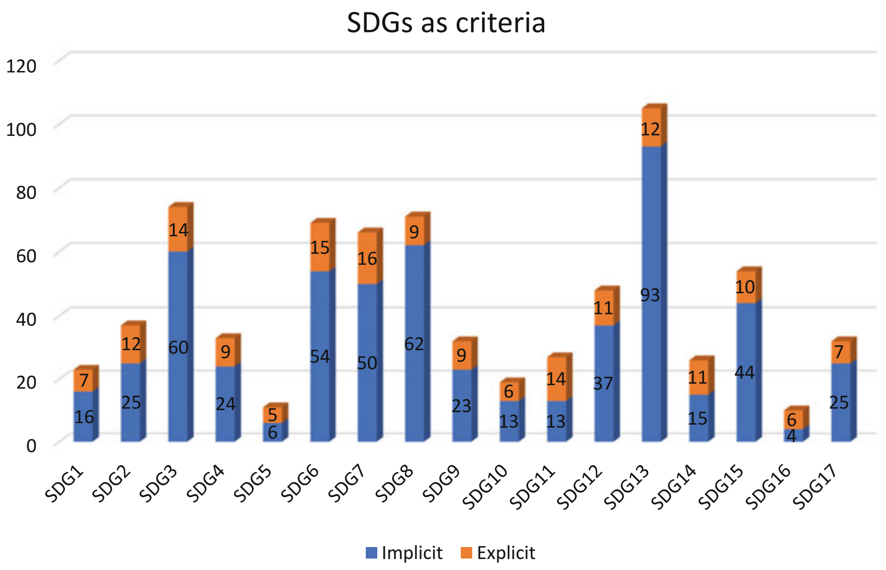


Fig. 2 Number of papers that examine each SDG as an MCDA criterion

Table 3 MCDA studies on SDGs with a focus on climate action (SDG 13)

Study	Method	Region	Focus area
Ahmed et al. (2020a)	Fuzzy AHP, fuzzy VIKOR	Pakistan	Re-examining the objectives of national climate policy
Ahmed and Mishra (2020)	AHP	Small Island developing states	Water-related challenges
Hassan et al. (2019)	MCDA	Pakistan	Energy and environmental security
Shem et al. (2019)	Weighted sum method	Vietnam	Policy portfolio evaluation for low carbon transition
Sanneh (2018)	Fuzzy AHP	Sub-Saharan Africa (with focus on Ghana and Senegal)	Prioritisation of climate change adaptation measures
Soni et al. (2017)	Fuzzy PROMETHEE	India (as part of the India-EU strategic dialogue)	Penetration of ICT and efficacy of e-governance across multiple sectors

10 (Reduced Inequalities) and 16 (Peace, Injustice and Strong Institutions) are assessed the least.

Less MCDA studies focus on SDGs as their focus area, instead of criteria (Fig. 3), explicitly focusing on specific SDGs. For instance, Budiman et al. (2017) assessed various poverty alleviation programs in Indonesia and identified eligible citizens to examine the impact of each scheme on fulfilling SDG 1 (poverty-related) targets, using a diverse combination of AHP, VIKOR, TOPSIS, PROMETHEE,

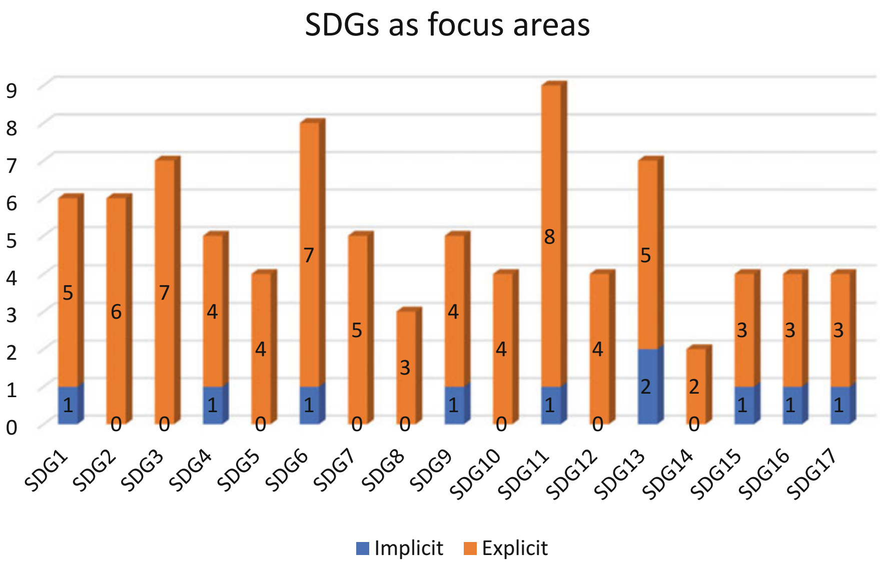


Fig. 3 Number of MCDA studies examining one or multiple SDGs as a focus area

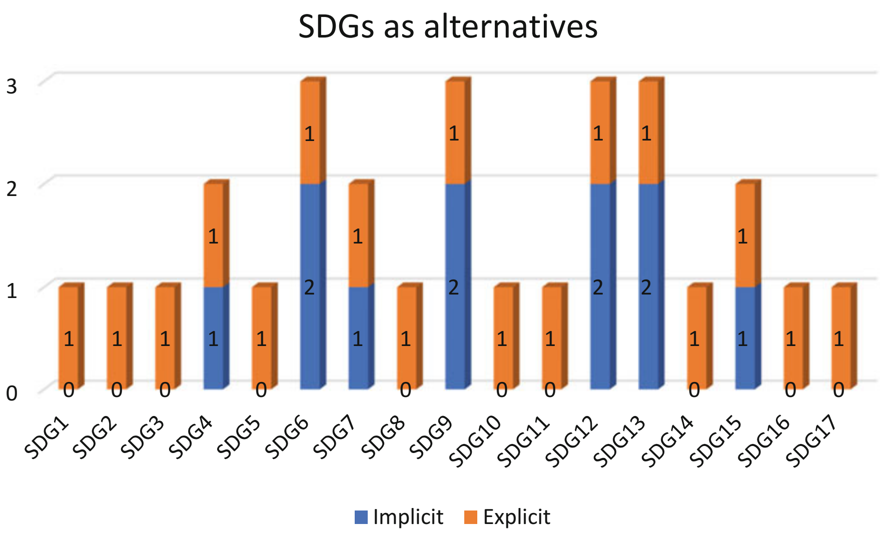


Fig. 4 Number of MCDA studies assessing one or more SDGs as an alternative

ELECTREE, SMART, and SAW. Similarly, Diaz-Sarachaga et al. (2017) proposed a new assessment framework for infrastructure investments in developing countries, which is one of the main subjects of SDG 9 (Industry, Innovation, and Infrastructure), using AHP and MIVES. In contrast, very few MCDA studies examined SDGs as alternatives (Fig. 4).

One the most direct attempts to treat SDGs as alternatives was performed by Zeug et al. (2019), who attempted to prioritise the SDGs based on the relevance of the corresponding sub-goals to bioeconomy; the ranking was produced from the aggregation of the evaluations of different stakeholders based on average values. Rampasso et al. (2019) examined Brazil's education and the insertion of sustainability in engineering curricula, which can be linked to SDG target 4.7, aiming to provide every person with relevant education; using TOPSIS, they evaluated ten challenges to introducing sustainability in engineering classes. Gupta and Singh (2020) introduced the Graph Theory Matrix Approach (GTMA) as a framework for assessing the sustainability of logistics service providers in India. Finally, D'Alpaos and Andreolli (2020) conducted a literature review regarding urban quality assessment to search for the most investigated aspects regarding the improvement of urban environment, with SDG-relevant aspects comprising their alternatives, which they evaluated with AHP across social, economic and environmental criteria.

3 Urgency of SDG Assessment, in Relation to Climate Policy, from the Experts' Point of View

3.1 Scope

In this section, we perform a multi-criteria analysis to evaluate stakeholders' assessments of climate action in relation to the sustainable development spectrum. In a regional workshop that was held in November 2019 in Brussels, Belgium, stakeholders were asked to contribute to responding to the research question: *"How urgent is it to assess each SDG in line with climate change and the Paris Agreement goals?"*. To achieve the objective of the study, the 2-tuple TOPSIS method is employed, coupled with a consensus measuring technique to increase robustness of the outcome and understand the dynamics between the different categories of stakeholders involved. The aim is to use the results of the MCDA analysis to inform the climate-economy modelling community on the most important SDGs that should be integrated in modelling exercises, and against progress on which climate action should be evaluated.

3.2 Context: Event, Alternatives and Criteria

The stakeholder engagement event was held as part of the "1st PARIS REINFORCE Stakeholder Council Dialogue workshop", entitled "Enhancing climate policy through co-creation", which took place on November 21, 2019, at the premises of Bruegel, in Brussels, Belgium. During the MCDA/SDG session, 31 participants

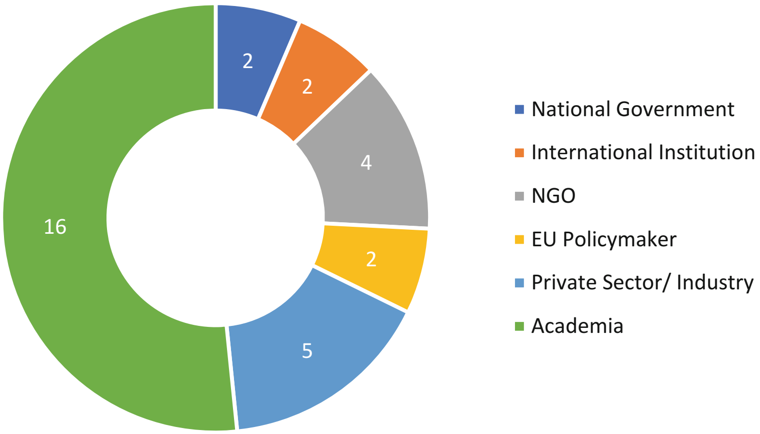


Fig. 5 Distribution of stakeholder groups

from different backgrounds and level of expertise (Fig. 5) were asked to evaluate the SDGs against a set of predefined criteria, using an online polling platform.

To engage with the research question of the study, the SDGs are placed as the alternatives of the analysis. Since the main objective of IAMs is to evaluate scenarios that assess the technological and economic feasibility of climate policy and goals (Ackerman et al., 2009), we axiomatically exclude SDG 13 from the analysis, when searching for additional SDGs to include in modelling activities. SDG 17, related to global partnerships and cooperation, is also excluded from the analysis as it falls outside the scope of integrated assessment modelling tools, which is to evaluate Paris Agreement pledges (Krey et al., 2019).

The stakeholders were asked to evaluate each SDG based on three criteria: importance, relevance to climate change, and trend of progress. These were selected on the basis of forming a consistent family of criteria that attempt to capture the broader viewpoint of the experts. Specifically, the "importance" criterion aims to capture a broad perception of the importance of fulfilling the targets of each SDG in society; relevance to climate change focuses more on the interlinkages between climate change and each of the other SDGs, reflecting whether an SDG should be examined coupled with climate goals. Finally, trend of progress aims to capture stakeholders' knowledge and perception of the improvements made so far towards achieving each SDG. The details on the formulation of the problem are presented in Table 4.

Due to the supplementary nature of the criteria, the resulting ranking is expected to reflect, from a stakeholders' perspective, the urgency to further study the integration of each SDG in modelling activities based on three key questions: how important is an SDG, how relevant to climate change is it and what is the progress so far? In line with the research question and to better express the urgency we adapt the last criterion to express the lack of progress. In that case an SDG receives the highest ranking and therefore the most urgent to study in models, when it is

Table 4 Alternatives and evaluation criteria used in the analysis

Alternatives	Evaluation criteria
SDG 1: No poverty	C1. Importance
SDG 2: Zero hunger	*How important do you find this SDG is to address?*
SDG 3: Good health and Well-being	{very low, low, moderate, high, very high importance}
SDG 4: Quality education	
SDG 5: Gender equality	
SDG 6: Clean water and sanitation	C2. Relevance
SDG 7: Affordable and clean energy	*How relevant to climate action do you think this SDG*
SDG 8: Decent work and economic growth	*is?*
SDG 9: Industry, innovation and infrastructure	{very low, low, moderate, high, very high relevance}
SDG 10: Reduced inequalities	
SDG 11: Sustainable cities and communities	
SDG 12: Responsible consumption and production	C3. Trend of Progress
SDG 14: Life below water	*How do you perceive the trend of progress in meeting*
SDG 15: Life on land	*the sub-goals of this SDG so far?*
SDG 16: Peace, justice and strong institutions	{very low, low, moderate, high, very high progress}

evaluated as important, relevant but at the same time there is limited progress in meeting the determined goals.

3.3 Methodology

3.3.1 The 2-Tuple Model

The results are displayed in a universal 5-term scale {very low, low, medium, high, very high}. These terms are closer to the natural language of the stakeholder in line with the computing with word methodology in sustainability decision making problems (Doukas et al., 2010), which increases the comprehensibility of the analysis outcomes. To fully exploit the linguistic terms, the 2-tuple model is used (Herrera & Martínez, 2000; Martinez & Herrera, 2012), which consists of a 2-tuple linguistic representation (s, a), where s is a linguistic term and a is a numeric value representing a symbolic translation to increase accuracy without overcomplicating the interpretation of the end result.

Let $S = \{s_0, \ldots, s_g\}$ be a linguistic term set and $\beta \in [0, g]$ be the result of a symbolic aggregation operation, where $g + 1$ is the cardinality of S. Let $i = round(\beta)$ and $\alpha = \beta - i$ be two values, such that $i \epsilon [-0.5,0, 5)$; then α is called a symbolic translation. The symbolic translation of a linguistic term s_i is a numerical value within $[-0.5{,}0,5)$ indicating the difference of the information between the calculated value $\beta \in [0, g]$, and its closest element within $\{s_0, \ldots, s_g\}$ indicating the content of the closest linguistic term S ($i = round(\beta)$).

In essence, the 2-tuple linguistic representation model extends the use of indexes modifying the fuzzy linguistic approach, by adding a symbolic translation that represents the linguistic information by means of a linguistic 2-tuple.

$$a = \begin{cases} [-0.5, 0.5), if\, s_i \in \{s_1, s_2, \ldots, s_{g-1}\} \\ [0, 0.5), if\ s_i = s_0 \\ [-0.5, 0), if\ s_i = s_g \end{cases}$$

Finally, for a linguistic term set $S = \{S_0, \ldots, s_g\}$ and a value supporting the result of a symbolic aggregation operation $\beta \epsilon\ [0, g]$, the 2-tuple expressing the equivalent information to β is calculated:

$$\Delta : [0, g] \rightarrow S \times (-0.5, 0.5)$$

$$\boldsymbol{\Delta}(\beta) = (s_i, \alpha), with \begin{cases} s_i \quad i = round\ (\beta) \\ \alpha = \beta - i \quad \alpha\epsilon[-0.5, 0, 5) \end{cases}$$

Evidently, the conversion of a linguistic term into a linguistic 2-tuple consists of adding a value 0 as symbolic translation: *si* ? *S* ⇒(*si*,0).

3.3.2 The 2-Tuple TOPSIS Model

As a ranking multicriteria methodology that calculates the distance of an alternative from a positive and a negative ideal solution, TOPSIS (Yoon & Hwang, 1981) has been found to perform significantly well in fuzzy systems with the extension of Fuzzy TOPSIS (Chen et al., 2006). It is also preferred and frequently employed in climate policy to handle uncertainty in relevant decision-making problems (Doukas & Nikas, 2020). In this study, the 2-tuple TOPSIS is used, combining the original TOPSIS method with the 2-tuple model. One of the first applications of a combination between 2-tuples and TOPSIS was performed by Doukas et al. (2010) to assess RES alternatives in the Greek electricity system, while the proposed framework was also later used to assess energy and environmental policies of Small-Medium Enterprises (Doukas et al., 2014), with 2-tuples allowing to present input and output data without affecting internal calculations of TOPSIS. The 2-tuple TOPSIS model was formally introduced by Wei (2010), where the proposed methodology was applied in an investment problem with multiple experts. To deal with the loss of linguistic interpretation, Sohaib et al. (2019) introduced a distance function in the calculation of the 2-tuple TOPSIS by setting different linguistic domains for the evaluation of the preferences, the weights, and the final distances. However, in decision making problems that include stakeholder engagement with feedback processes, using three different linguistic domains may be technically correct from a modelling perspective but create difficulties in stakeholders to quantify the final results, thus affecting their ability to translate them into action. Although the addition of the distance function is a useful tool to distinguish between the interpretation of initial preferences and final distances, defining strictly different domains to evaluate them is not necessary, as long as the distance function is properly handled. Labella et al. (2020) followed the methodology introduced by Sohaib et al. (2019), including the distance function, but the same general 5-scale term was used both for the preferences and the calculation of the distances. Understanding that the terms in the two scales may be the same but used to express different variables allowed the mapping of each value in a universal domain without disturbing linguistic interpretability. Here, we argue that the approach used in Labella et al. (2020) is better suited for climate policy problems with stakeholder engagement to allow them to compare the results in the values in which they provided the initial input. Therefore, in this study we use the methodology followed by Labella et al. (2020), described below:

(i) Defining a weight vector $U_t = \left(u_j^t\right)^T_{1*n}$, where $u_j^t \in U$ is the linguistic preference by stakeholder e_t for criterion c_j and U is a linguistic term set, with $U = \{u_1, u_2, \ldots, u_p\}$ transformed into a 2-tuple linguistic decision matrix $U_t = \left(u_j^t, 0\right)^T_{1*n}$.

(ii) Calculating the normalised 2-tuple weight vector $U_t^N = \left(\overline{u}_j^t, \overline{\beta}_j^t\right)^T_{1*n}$ for each stakeholder e_t as $\left(\overline{u}_j^t, \overline{\beta}_j^t\right) = \Delta_u\left(\frac{\Delta_u^{-1}\left(u_j^t, 0\right)}{T_U - 1}\right), j = 1, 2, \ldots, n$ and T_U is the cardinal of set U.

(iii) Defining the decision matrix $X_t = \left(r_{ij}^t\right)_{m*n}$, where $\left(r_{ij}^t\right) \in S$ is the linguistic value preference provided by stakeholder e_t for alternative a_i over criterion c_j, and S is the linguistic term set, with $S = \{s_1, s_2, \ldots, s_t\}$ transformed into a 2-tuple linguistic decision matrix $X_t = \left(r_{ij}^t, 0\right)_{m*n}$.

(iv) Calculating the weighted decision matrix $\overline{X}_t = \left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right)_{m*n}$ for each stakeholder e_t, with- $\left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right) = \Delta_S\left(\Delta_u^{-1}\left(\overline{u}_j^t, \overline{\beta}_j^t\right) . \Delta_S^{-1}\left(r_{ij}^t, 0\right)\right), i = 1, 2, \ldots, m, j = 1, 2, \ldots, n.$

(v) Calculating the positive and negative ideal solutions for each stakeholder e_t as: $\left(r^{t,+}, \alpha^{t,+}\right) = \left\{\left(r_1^{t,+}, \alpha_1^{t,+}\right), \left(r_2^{t,+}, \alpha_2^{t,+}\right), \ldots, \left(r_n^{t,+}, \alpha_n^{t,+}\right)\right\}$ and $\left(r^{t,-}, \alpha^{t,-}\right) = \left\{\left(r_1^{t,-}, \alpha_1^{t,-}\right), \left(r_2^{t,-}, \alpha_2^{t,-}\right), \ldots, \left(r_n^{t,-}, \alpha_n^{t,-}\right)\right\}$, where $\left(r_j^{t,+}, \alpha_j^{t,+}\right) = \max_i\left\{\left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right) \middle| c_j \in B\right\}$ *or* $\min_i\left\{\left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right) \middle| c_j \in B'\right\}$ and $\left(r_j^{t,-}, \alpha_j^{t,-}\right) = \min_i\left\{\left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right) \middle| c_j \in B\right\}$ *or* $\max_i\left\{\left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right) \middle| c_j \in B'\right\}$, where $i = 1, 2, \ldots,$

m, $j = 1, 2, \ldots, n$ and where B and B' are the benefit and cost criteria sets respectively.

(vi) Determining the distance of each alternative form the positive and negative ideal solutions for each stakeholder e_t as: $\left(\xi_i^{t,+}, \eta_i^{t,+}\right) = \Delta_{S'}\left(\frac{1}{n}\sum_{j=1}^{n}\frac{(T_{S'}-1)}{(T_S-1)}\cdot\left(|\Delta_S^{-1}\left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right) - \left(r_j^{t,+}, \alpha_j^{t,+}\right)|\right)\right)$ and $\left(\xi_i^{t,-}, \eta_i^{t,-}\right) = \Delta_{S'}\left(\frac{1}{n}\sum_{j=1}^{n}\frac{(T_{S'}-1)}{(T_S-1)}\cdot\left(|\Delta_S^{-1}\left(\overline{r}_{ij}^t, \overline{a}_{ij}^t\right) - \left(r_j^{t,-}, \alpha_j^{t,-}\right)|\right)\right)$, where $S' = \left\{s'_1, s'_2, \ldots, s'_{t'}\right\}$ is the linguistic term set for the distances, T_S and $T_{S'}$ the cardinals of sets S and S' respectively.

(vii) Calculating the relative closeness degree of each alternative from the positive ideal solution for each stakeholder e_t as: $\left(\xi_i^t, \eta_i^t\right) = \Delta_{S'}\left(\left(\frac{\Delta_{S'}^{-1}\left(\xi_i^{t,-}, \eta_i^{t,-}\right)}{\Delta_{S'}^{-1}\left(\xi_i^{t,+}, \eta_i^{t,+}\right) + \Delta_{S'}^{-1}\left(\xi_i^{t,-}, \eta_i^{t,-}\right)}\right)\cdot(T_S - 1)\right)$, $i = 1, 2, \ldots, m$ *and* T_S the cardinal of set S. In the current form the results are expressed in the linguistic scale S used by the stakeholders to increase interpretability. The results could have been displayed in the scale S' which was defined explicitly to express distances, however presenting the results in the new terms, despite been more appropriate, could confuse the stakeholders.

(viii) Computing the collective 2 tuple linguistic decision matrix $X = (\widetilde{r}_{it}, \widetilde{\alpha}_{it})_{m*k}$, where $(\widetilde{r}_{it}, \widetilde{\alpha}_{it}) = \left(\xi_i^t, \eta_i^t\right)$, $i = 1, 2, \ldots, m, t = 1, 2, \ldots, k$. In this step the stakeholders are considered equally weighted. By adjusting steps 1–4, the new matrix X could be calculated to also include weights for the expert.

(ix) Calculating the positive and negative ideal collective as: $(r^+, \alpha^+) = \left\{\left(r_1^+, \alpha_1^+\right), \left(r_2^+, \alpha_2^+\right), \ldots, \left(r_k^+, \alpha_k^+\right)\right\}$ and $(r^-, \alpha^-) = \left\{\left(r_1^-, \alpha_1^-\right), \left(r_2^-, \alpha_2^-\right), \ldots, \left(r_k^-, \alpha_k^-\right)\right\}$, where $\left(r_t^+, \alpha_t^+\right) = \max_i\left\{(\widetilde{r}_{it}, \widetilde{\alpha}_{it}) \times |c_j \in B\right\}$ *or* $\min_i\left\{(\widetilde{r}_{it}, \widetilde{\alpha}_{it})|c_j \in B'\right\}$ and $\left(r_t^-, \alpha_t^-\right) = \min_i\left\{(\widetilde{r}_{it}, \widetilde{\alpha}_{it}) \times |c_j \in B\right\}$ *or* $\max_i\left\{(\widetilde{r}_{it}, \widetilde{\alpha}_{it})|c_j \in B'\right\}$, where $i = 1, 2, \ldots, m$, $t = 1, 2, \ldots, k$ and B and B' are the benefit and cost criteria sets respectively.

(x) Determining the distance of each alternative form the positive and negative ideal solutions for each stakeholder t as: $\left(\xi_i^+, \eta_i^+\right) = \Delta_{S'}\left(\frac{1}{k}\sum_{t=1}^{k}\frac{(T_{S'}-1)}{(T_S-1)}\cdot\left(|\Delta_S^{-1}(\widetilde{r}_{it}, \widetilde{\alpha}_{it}) - \left(r_t^+, \alpha_t^+\right)|\right)\right)$ and $\left(\xi_i^-, \eta_i^-\right) = \Delta_{S'}\left(\frac{1}{k}\sum_{t=1}^{k}\frac{(T_{S'}-1)}{(T_S-1)}\cdot\left(|\Delta_S^{-1}(\widetilde{r}_{it}, \widetilde{\alpha}_{it}) - \left(r_t^-, \alpha_t^-\right)|\right)\right)$, where $S' = \left\{s'_1, s'_2, \ldots, s'_{t'}\right\}$ is the linguistic term set for the distances, T_S and $T_{S'}$ the cardinals of sets S and S' respectively.

(xi) Finally, calculating the relative closeness degree of each alternative from the positive ideal solution as: $(\xi_i, \eta_i) = \Delta_{S'}\left(\left(\frac{\Delta_{S'}^{-1}(\xi_i^-, \eta_i^-)}{\Delta_{S'}^{-1}((\xi_i^+, \eta_i^+)) + \Delta_{S'}^{-1}(\xi_i^-, \eta_i^-)}\right) \cdot (T_S - 1)\right), \quad i = 1, 2, \ldots, m \; and \; T_S$ the cardinal of set *S*. The results could have been displayed in the distance scale S′, but instead they are converted to the scale the stakeholders provided their answers in for clarity of results, needed in the next steps.

As evident from the description of the framework steps, two rounds of 2-tuple TOPSIS are used in line with the approach suggested by Krohling and Campanharo (2011) for fuzzy TOPSIS, and then extrapolated for behavioural and 2-tuple TOPSIS (Nikas et al., 2018; Labella et al., 2020). The first round calculates an initial solution independently for each stakeholder and then, from the intermediate results, a new matrix is formed, where 2-tuple TOPSIS is again applied, with stakeholders being the "criteria" of the new TOPSIS model.

3.3.3 Consensus Measuring

In group decision making problems, dissimilarities may exist between individual answers and the collective solution. Experts from different backgrounds, like in this study, tend to evaluate alternatives differently representing a variety of perspectives and interests. To measure these different assessments, Kacprzyk and Fedrizzi (1986) introduced the concept of "soft" consensus as a metric to capture and calculate the level of dissimilarity, since reaching total consensus is usually not possible. Consensus measuring techniques, either independently or as part of complete consensus reaching processes that include feedback mechanisms, have played an important role in group decision making, especially when including linguistic variables (Herrera et al., 1996). To calculate consensus, usually two approaches are followed (Dong et al., 2018); the preferences of stakeholders are compared either with one another in pairs (e.g. Palomares et al., 2013) or with a collective solution (e.g. Ben-Arieh & Chen, 2006). Herrera-Viedma et al. (2002) argued that, by comparing a collective solution with individual preferences, it is possible to capture differences in rankings rather than evaluations, avoiding overevaluating different assessments that lead to similar rankings. Labella et al. (2020) extended this approach by using the evaluation of the 2-tuple TOPSIS as a collective solution to weigh the distances from individual preferences, capturing both differences in rankings and exact numerical dissimilarities. Overall, a lot of different consensus measuring models exist, with Palomares et al. (2014) mapping them based on the processes followed, to state that it is imperative not only that models be created or compared, but also that the suitability of a model to solve specific types of group decision making problems be described. The model proposed in Labella et al. (2020), already used for risk assessment of a sustainability transition, is found appropriate to deal with climate policy group decision problems with multiple stakeholders. In such problems, due to the conflicting nature of interests among the different groups participating, usually it is not always the purpose of the process to force a consensus solution that would be very difficult to implement, but to understand the different dynamics among the participants. For that purpose, a framework that employs a ranking MCDA model to arrive to an initial solution and then calculates a consensus measure to increase robustness of such solution and allow further processing to identify where each group stands, can act as a first step in the efforts to increase climate science diplomacy (Nikas et al., 2020a) and co-ownership. The steps of the consensus measuring model are described below:

(i) The dissimilarity of each expert for each alternative $p_i(x_j)$ is calculated by comparing the distance between the result of the 2-tuple TOPSIS of that alternative in the experts' individual solution and in the collective one as follows: $p_i(x_j) = p(R^i, R^c)(x_j) = \left(\frac{|R^c_j - R^i_j|}{T-1}\right)^b \in [0, 1], \quad b \geq 0$, where i stands for each expert, j stands for each alternative, b can be in the range of (0,1) to control the rigorousness of the model, R^c_j is the result of the 2-tuple TOPSIS of the alternative j in the group solution, R^i_j is the result of the 2-tuple TOPSIS of the alternative j in expert's i solution, and T the cardinal of the linguistic term set, used to normalise the dissimilarity values.

(ii) Next, we calculate the consensus degree of all experts on each alternative x_j using the following expression $C(x_j) = 1 - \sum_{i=1}^{m} \frac{p_i(x_j)}{m}$, where m stands for the total number of experts.

(iii) Finally, we calculate the consensus measure over the set of alternatives, called C_X: $C_X = \frac{\sum_{j=1}^{k} C(x_j) * R^C_j}{\sum_{j=1}^{k} R^C_j}$, where k is the total number of alternatives. In this approach the aggregation is performed through a weighted average formula, where the evaluation of the 2-tuple TOPSIS of the global solution for each alternative is used as the weight of the consensus degree over this alternative.

(iv) Applying a similar approach with the consensus measure, the proximity of i-th expert to the global solution can be calculated: $P^i_X = \frac{\sum_{j=1}^{k} (1 - p_i(x_j)) * R^C_j}{\sum_{j=1}^{k} R^C_j}$

3.4 Results

During the workshop, the 31 participants provided their assessments of the 15 SDGs included in this study, based on the three criteria and the corresponding questions described in Table 4. As already explained, the answers are converted in a common five-term linguistic scale {very low, low, medium, high, very high}, while the

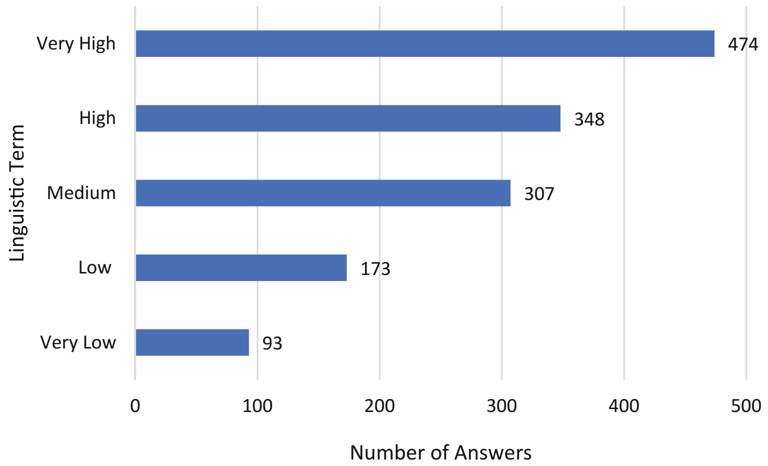


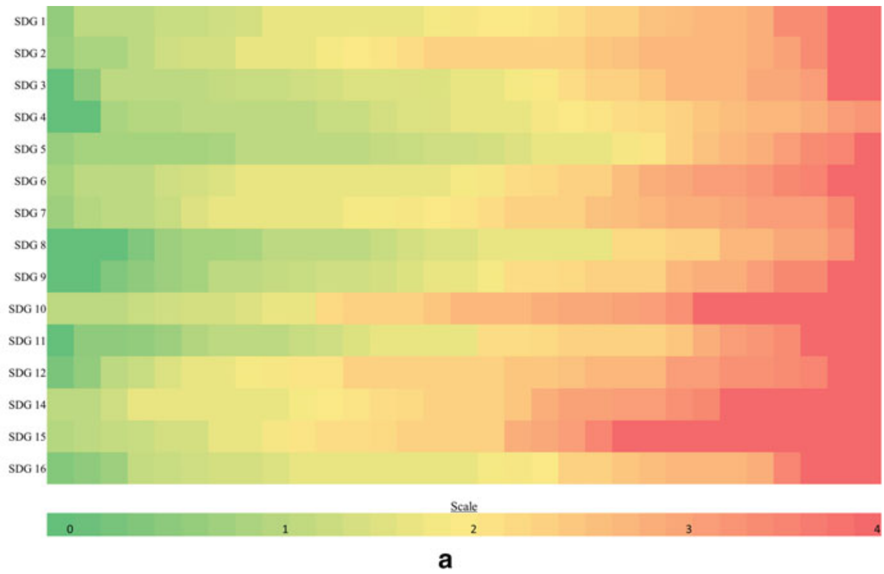
Fig. 6 Distribution of assessments in the linguistic scale

answers on the third criterion of progress are inverted to express the lack of progress. By combining all the criteria, we can calculate the urgency to study each SDG in climate policy modelling exercises. Figure 6 illustrates the distribution of the answers in the linguistic scale.

The importance of the SDGs and the necessity to continue progressing towards meeting the goals is already evident. The stakeholders' answers tend to be in the higher end of the scale with "high" and "very high" assessments dominating almost 58% of the total answers and the average value being (High, −0.33), despite decision makers in general following a more moderate behaviour (Mascarenhas et al., 2014) and/or preferring moderate alternatives (Chen et al., 2020). Even though this is an initial step of the analysis, these answers could be interpreted as a general interest of the stakeholders in the integration of SDGs in models and the insights such exercises can provide.

The input is then inserted in the 2-tuple TOPSIS model described in Sect. 3.3.2. After the first round of analysis, a final assessment of the SDGs is carried out for each stakeholder individually. To visualise this intermediate output, we rank the assessments of the stakeholders per SDG to produce the heatmap presented in Fig. 7a. The heatmap provides us with a first impression on the urgency of each SDG in the assessment of the stakeholders, while the corresponding breakdown of the results highlights some tendencies of each group (Fig. 7b).

In particular, SDGs 14 and 15 seem to concentrate the highest values, indicating a first preference of the stakeholders for issues related to life below water and on land, being concerned about the effect of climate change on the life cycles of plants and animals. Reduced Inequalities (SDG 10) also seem to be an important priority of the stakeholders with almost two-thirds of the evaluations being in the higher end of the scale. However, although general inequalities were assessed as important, with stakeholders understanding that the effects of climate change can be harsher on



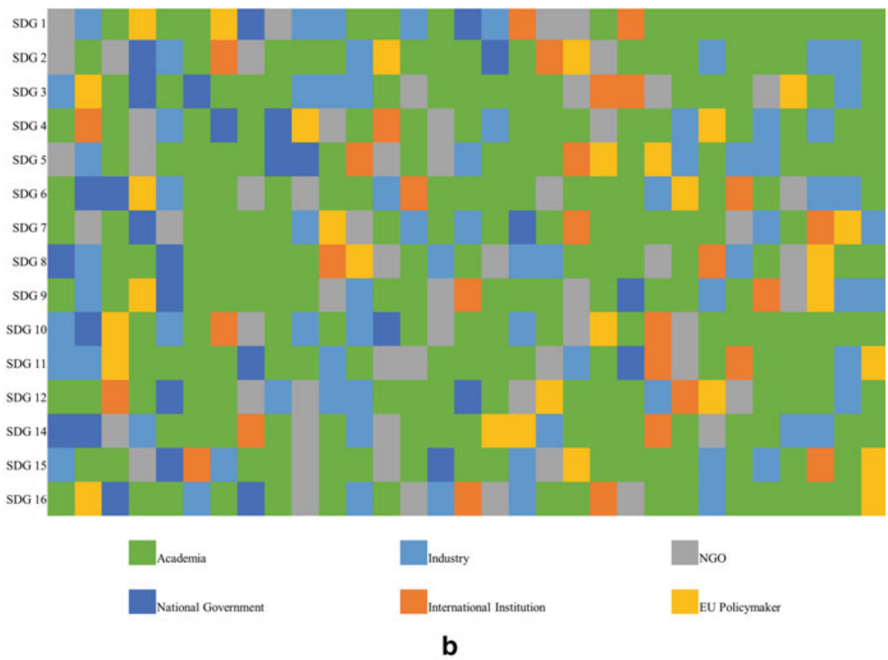


Fig. 7 (**a**) SDG urgency heatmap and (**b**) group breakdown of assessments after the first round of 2-tuple TOPSIS

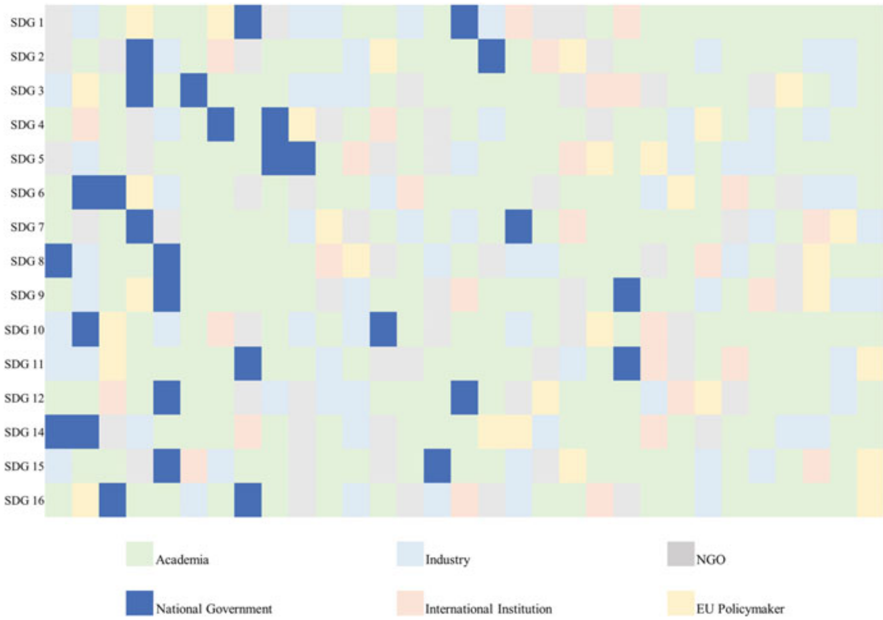


Fig. 8 SDG assessments by national government representatives

certain societal groups, gender inequalities (SDG 5) received lower evaluations, possibly reflecting knowledge of limited capabilities of modelling frameworks to look into gender issues and therefore lower expectations.

Most stakeholder groups showed variance in the evaluations among the members of each group, with the answers of the stakeholders being spread in the entire range of the scale of the map (Fig. 7b). This deviation is expected, especially in the groups represented by more participants (e.g. academia). Notably, however, two groups showed patterns in their assessments. Members from international institutions provided evaluations that are placed slightly higher on the map, while on the contrary most evaluations from national policymakers were placed in the lower terms, with very few exceptions breaking through the other end; Fig. 8 enhances the evaluations of national policymakers. This is also evident from the fact that after averaging the answers of the stakeholders, coming from national governments, no SDG received an assessment of more than (medium, 0.23), possibly reflecting either a sense of comfort with the progress made in each SDG and with the need for further analysis and/or a dedicated focus on climate change and action per se.

After the intermediate outputs, the SDG ranking and evaluation of each stakeholder is used in a new round of 2-tuple TOPSIS, as described in Sect. 3.3.2, to produce the collective solution of the group. The final ranking is presented in Table 5 and Fig. 9.

Results of the second step of the analysis validate previous insights, with 4 out of the 15 SDGs being assessed with a “high” evaluation, ten receiving evaluations

Table 5 Final prioritisation of the SDGs from the engaged group of stakeholders

Ranking	Evaluation
SDG 15: Life on land	(High, 0.05)
SDG 14: Life below water	(High, −0.02)
SDG 10: Reduced inequalities	(High, −0.08)
SDG 12: Responsible consumption and production	(High, −0.32)
SDG 2: Zero hunger	(Medium, 0.44)
SDG 7: Affordable and clean energy	(Medium, 0.42)
SDG 6: Clean water and sanitation	(Medium, 0.4)
SDG 1: No poverty	(Medium, 0.26)
SDG 16: Peace, justice and strong institutions	(Medium, 0.21)
SDG 11: Sustainable cities and communities	(Medium, 0.08)
SDG 3: Good health and Well-being	(Medium, −0.01)
SDG 9: Industry, innovation and infrastructure	(Medium, −0.12)
SDG 4: Quality education	(Medium, −0.29)
SDG 5: Gender equality	(Medium, −0.33)
SDG 8: Decent work and economic growth	(Low, 0.45)

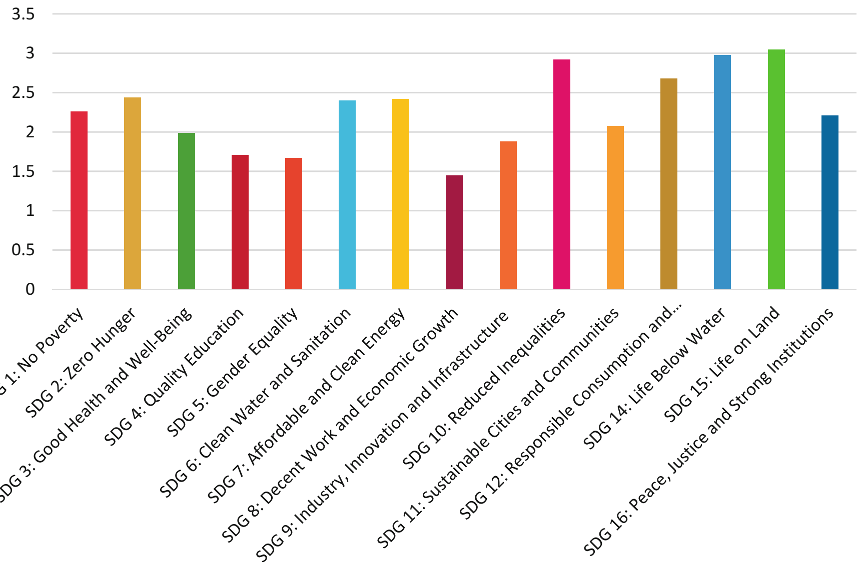


Fig. 9 Final ranking and evaluations of the SDGs

around "medium", and only one receiving a "low" evaluation. As previously discussed, life on land, life below water and reduced inequalities were prioritised, with responsible consumption and production—frequently associated with climate change—also performing well. On the other hand, decent work and economic growth failed to gather attention, with stakeholders either considering it as less important than others or reflecting that there is already good progress towards this goal. It is also evident from the results that stakeholders prioritised SDGs covering aspects on which the impact from climate change is more evident, while SDGs with less profound links with climate change, like gender equality or quality education, fell behind in the ranking.

We already observed that certain groups display different evaluation patterns. From that perspective, it is interesting to calculate the collective solution of each group independently. For that reason, using APOLLO (Labella et al., 2020), the second round of 2-tuple TOPSIS is repeated for each group, this time including only the members of the group itself. Since the idea behind TOPSIS is to compare alternatives to a positive and negative ideal solution, which are defined internally in the framework, and given that the runs were independent for each group, the results should not be interpreted as a direct quantitative comparison of the assessments, but only to compare the order they produce for each group. In Fig. 10 the results of this process are presented without a linguistic scale to avoid misinterpretation.

Despite significant differences between the groups, in five of the six groups the first SDG in the ranking is one of the four that received a "high" evaluation in the collective solution (SDGs 10, 12, 14, 15). This provides a first indication of the consensus among the group about which SDGs are considered a priority in studying through modelling activities, since they received high evaluations in most groups despite their final order. Alterations in the ranking of SDGs with medium initial priority were expected since each group evaluates based on different viewpoints. Similarly, a consensus also seems to exist regarding the lowest priorities, with SDGs 4 and 8 underperforming in most groups.

Having acquired a qualitative assessment of the consensus of the group and especially the highest and lowest priorities, we calculate the consensus measure based on the framework described in Sect. 3.3.3. Comparing the prioritisation of each expert from the first round of TOPSIS with the collective prioritisation from the second round, the level of consensus is estimated at 81.4%. Based on this, the proximity level between each individual stakeholder and the collective solution is presented in Fig. 11.

From Fig. 11, we can observe that the range of proximity levels is among 69% (Stakeholder #25) and 90% (Stakeholder #15), indicating significant differences among the stakeholders. To capture these differences in the preferences of the groups of stakeholders, we independently compare the stakeholders in each group with the collective solution. For example, to calculate the group consensus level of academia, we include only the stakeholders of this group and compare them with the global solution. This process is repeated for each group. Additionally, from the independent group solutions presented in Fig. 11, we calculate an internal consensus level comparing this group solution with the solutions of the stakeholders of the group. The first measure is an indication of how close the stakeholders of each group are with the collective solution, while the second indicates how close the members of each group are with one another. The results are presented in Fig. 12.

Expectedly, internal consensus is higher than the group consensus level with the collective solution in all groups. Industry representatives as well as EU and national

Fig. 10 Independent prioritisation of the different stakeholder groups

policymakers had lower consensus than the total, while NGOs had the highest level, with members from academia and international institutions being around the average value. Members from NGOs, international institutions and national governments had very high levels of internal consensus, which for the latter led to the highest difference between the consensus on the collective solution and the internal consensus.

3.5 Discussion

This study attempted to answer a key research question of how urgent climate stakeholders believe it is to incorporate SDGs in climate- and energy-economy modelling exercises by prioritising them based on their perceived importance, relevance to climate change, and progress achieved so far. Early in the analysis, it became evident that the engaged stakeholders considered that further studying SDGs

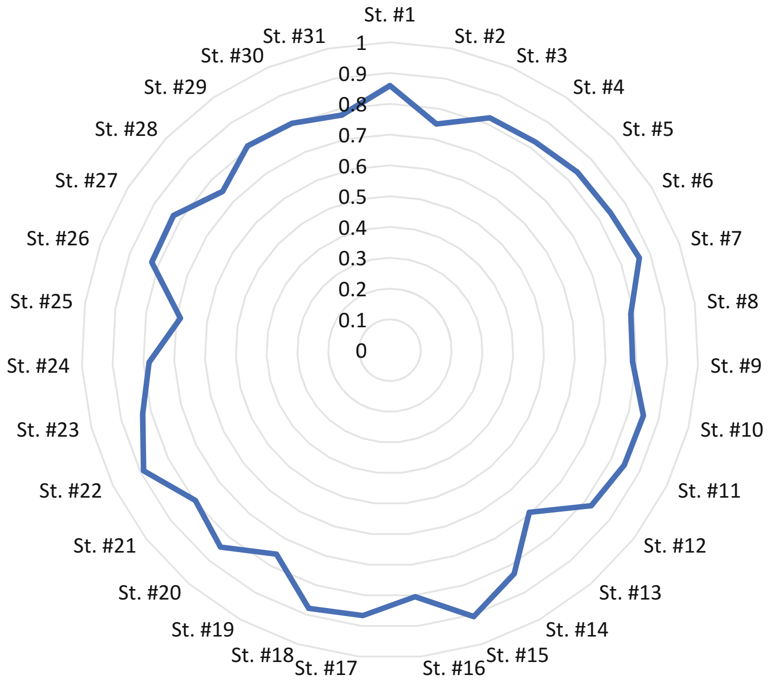


Fig. 11 Proximity level of each stakeholder with the collective solution

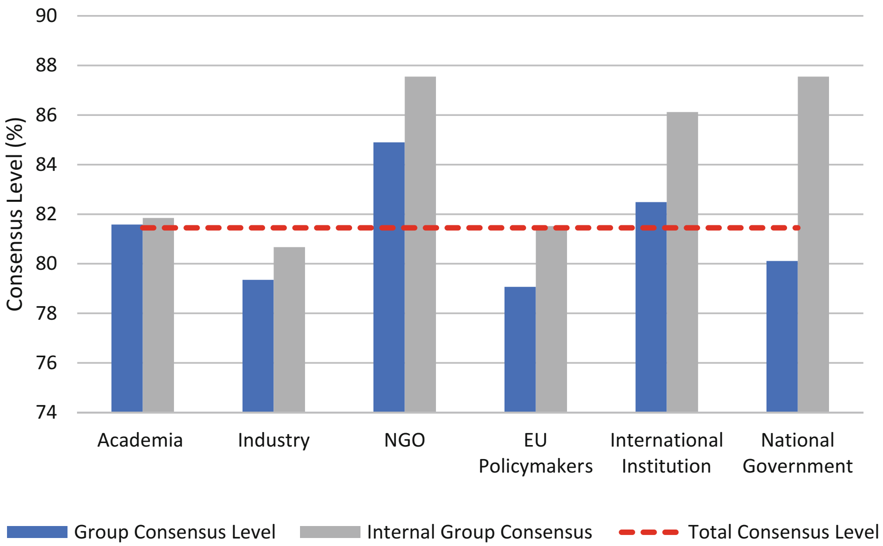


Fig. 12 Group consensus level with collective solution and internally

in relation to climate change is critical. Most of their initial answers were concentrated towards the higher end of the linguistic scale, with the "very high" term receiving the most answers. This indicates that stakeholders not only believe that SDGs are important and relevant to climate change and action, but also that until now limited progress has been made in achieving meeting them. Given a general tendency of stakeholders to follow a moderate behaviour and avoid extreme values of the scale, these high ratings provide a first indication that climate stakeholders are highly interested in integrating SDGs more in modelling exercises.

Both from the intermediate multicriteria analysis and the final ranking, a preference can be deduced regarding SDGs 10, 12, 14, and 15, which received high evaluations from the majority of the stakeholders, as evident in the heatmap and an evaluation around "high" in the final ranking. In fact, life on land and below water (SDGs 15 and 14) were prioritised the most, indicating that stakeholders are mostly concerned about the effects of climate change on ecosystems and biodiversity, as well as how human behaviour affect the broader environment and life on it, especially correlated with how humans treat resources (SDG 12). This output is interesting as few modelling studies are found to have analysed impacts on biodiversity, while SDGs related to inequalities are not well covered in modelling studies, apart from a limited number of indicators (van Soest et al., 2019). On the latter front, the connection between broader and gender inequalities as well as poverty and the increase of vulnerabilities caused from climate change creates an interlinkage between SDGs 1, 5 and 10 (UNESCO, 2017). However, in this study stakeholders' evaluations showed a large spread in the scale for these SDGs, with reduced inequalities ranking high, poverty eradication in the middle, and gender inequalities in the bottom. This difference is prone to two interpretations. First, it could express a genuine preference of SDG 10 as more important than the others, implying that by focusing on achieving broader social equality targets will promote progress in the others; but it could also reflect misconceptions and lack of knowledge about broader effects of climate change in societal issues. Considering that reduced inequalities indeed ranked high in the prioritisation leads to the conclusion that stakeholders do not ignore inequality issues altogether but provided a preference of what they consider most important to integrate in the formalised modelling frameworks. The overall analysis may reflect that stakeholders chose to emphasise what is hitherto overlooked in modelling studies (e.g. SDGs 14 and 15), instead of aspects that are by default included in these studies (e.g. SDG 8). Despite the latter's widely acknowledged importance in promoting sustainable work and growth, this result adds to the debate on whether SDG 8 adequately focuses on decent work without conflict with the entire agenda (Rai et al., 2019). More co-creation studies with stakeholders could shed light on the reasons behind the experts' preferences, especially when related with different evaluations for SDGs with evident synergies, as our study hints that modelling activities do not seem to adequately consider stakeholders preferences.

To increase robustness of the final calculated ranking, the consensus level was also measured, at 81.4%, indicating a significant level of agreement despite the divergence of the stakeholders' backgrounds, enhancing the output that the four SDGs identified with a high evaluation are the majority's preferences. Despite this agreement, fluctuations of both the ranking and the evaluations are present among the different groups. The most notable example lies in the results of the national policymaking group, with assessments concentrated in the lower end of the scale. While the consensus of the group with the global solution was below average, internal consensus was very high at around 87%. With concerns rising over the progress on achieving the targets of the goals (Sachs et al., 2019), this result opens the question on whether national governments are fully committed to achieving sustainability or even understanding the importance of following up on the 2030 Agenda.

4 Conclusions

This study attempted to prioritise SDGs based on the evaluations of 31 stakeholders from different backgrounds in order to shed light on which SDGs they consider most urgent to study in modelling activities. This necessity derives from a systematic literature review, which identified that modelling exercises have difficulties representing SDGs and only achieve so through sub-goals and approximate metrics. Similarly, a lack of studying SDG directly as MCDA alternatives is reflected in the small number of such studies, in which in fact SDGs are mostly referred to implicitly. Therefore, to achieve the purpose of the analysis, a group decision making framework was employed based on the 2-tuple TOPSIS model that uses linguistic variables, which are closer to the language that experts are more comfortable using, and further enhanced using consensus measuring calculations to improve robustness of the outputs. The SDGs are inserted in the analysis as alternatives with the aim to prioritise them based on their importance, relevance to climate change and achieved progress so far. Due to the high evaluations that the stakeholders provided, we concluded that they collectively consider SDGs to be a very critical part of future modelling exercises. A key output of the analysis was that a select few SDGs (15, 14, 10, 12) on life below water and on land, equality and responsible production and consumption were the most vital from the stakeholders' point of view. Despite fluctuations among the rankings of the different groups, these SDGs performed consistently high, with a consensus of 81.4%. Another interesting output was the fact that national governments representatives participating in the workshop tended to evaluate the importance of integrating SDGs in climate policy modelling analysis significantly lower than the rest of the groups, possibly reflecting the determination or ability of EU national governments to align national Paris Agreement-compliant pathways with the sustainability agenda.

The study can provide valuable insights for future research. Modelling activities can be informed by the results and place more importance in including and representing the SDGs that the stakeholders considered as more important: significant efforts are placed in improving modelling capacity (Nikas et al., 2021); adding complexity to integrate everything in one-size-fits-all approaches may prove infeasible, but focusing on aspects that stakeholders and policymakers themselves deem critical paves a technically more realistic way. Additionally, this study can be further improved by including more regions especially from developing countries to capture different needs and approaches. This could also increase the number of participants, further increasing the robustness of the results and validating the tendencies observed in groups with a small number of participants.

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Multicriteria Decision Support for Sustainable Energy Systems

Carlos Henggeler Antunes

Abstract *Ensuring access to affordable, reliable, sustainable and modern energy for all* is one of the 17 Sustainable Development Goals (SDG), which are the heart of the 2030 Agenda for Sustainable Development adopted by all United Nations Member States in 2015. SDG are an urgent call for action, requiring effective decision support processes to select, rank or categorize feasible courses of action. Sustainability is intrinsically a multidimensional concept, the embodiment of which calls for multicriteria decision support approaches capable of consistently encompassing economic, environmental, and social features. Therefore, the explicit consideration of multiple, conflicting and incommensurate evaluation aspects is essential to reach balanced and acceptable decisions. This paper aims to put in perspective the added value that multicriteria models and methods can offer to support sound and sensible decisions having energy systems at the heart, with challenging implications in multiple domains due to the pervasiveness of energy as a factor of prosperity.

Keywords Multicriteria decision aid · Energy sector · Sustainable development

1 Introduction

The provision of affordable, reliable, and sustainable forms of energy is crucial to supply diversified demand for energy services in all economic sectors as a factor of prosperity and well-being. This is recognized in the Sustainable Development Goal (SDG) 7, in the framework of the 2030 Agenda for Sustainable Development adopted by all United Nations Member States in 2015. This goal is strongly intertwined with other SDG as: building resilient infrastructure and promoting

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sustainable industrialization; making cities inclusive, safe, resilient and sustainable; protecting, restoring and promoting sustainable use of ecosystems.

The need for energy is pervasive in everyday life, from supplying power and heat to production systems to satisfying heating, cooling, lighting, and mobility needs. The increasing concerns with the environmental impacts associated with the entire energy supply chain, from extraction of raw materials to end-use, compels considering evaluation aspects of the merit of solutions well beyond the classic models of cost minimization subject to demand satisfaction and technology constraints in energy planning. Therefore, emissions, land use, impacts on ecosystems, reliability of supply, source diversification, external dependency, etc., have gained a relevant role in shaping and assessing energy decisions embracing a broader societal perspective. These decisions may be made at different levels from strategic to operational and with different timeframes (e.g., from long-term power system planning to real-time end-user consumption schedule), often accounting for intergenerational effects associated with large investments and environmental impacts.

With the energy crisis in the 1970s, optimization models originally driven by cost minimization objective functions began to include other concerns, namely related to environmental impacts. However, these aspects were first accounted for using some type of monetization of their effects, for instance by assigning a cost to emissions that was then integrated in an overall cost function. In this way, aspects of different nature were expressed in the same monetary dimension, but hiding their conflicting nature and the tradeoffs at stake, thus implicitly assuming a compensatory stance that could not be accepted in practice. Therefore, multicriteria and multiobjective models and methods have been recognized as the most suited approaches to offer sound decision support in a large variety of problems in the energy sector, due to their capability to include coherently the multiple, conflicting and incommensurate evaluation aspects as objective functions in multiobjective optimization (MOO) models and criteria in multicriteria decision analysis (MCDA).[1] The reasons to use MOO/MCDA approaches should be understood beyond the "realistic" argument, i.e., the world is multidimensional, but additionally they offer a modeling and methodological framework enabling to explore a richer universe of potential solutions and analyze the tradeoffs between the competing evaluation axes to reach balanced solutions. Furthermore, MOO/MCDA approaches contribute to combat the myth of "aseptic" decision procedures, in the sense that the perspectives, interests and preference of the multiple stakeholders should be integrated into the decision support process by means of meaningful technical parameters consistently

[1]At a broader categorization level, models and methods can be considered devoted to multiobjective optimization (MOO) and multicriteria decision analysis (MCDA). In MOO, mathematical programming models involve multiple objective functions to be optimized in a feasible region defined by a set of constraints, with different types of decision variables (binary, integer, continuous). In MCDA, a limited number of alternatives (options) are explicitly known a-priori to be evaluated according to multiple criteria, typically departing from a bidimensional impact matrix (alternatives vs. criteria) displaying the performances of the alternatives using different types of scales (ratio, interval, etc.).

conveying that information into the operational framework of the methods. This methodological and operational paradigm contributes to increase acceptance and robustness of recommendations.

The energy transition underway refers to the transformation process of the global energy sector from fossil-based generation and consumption to zero-carbon, as an essential contribution to curb global warming and climate change. The key drivers of the energy transition are the increasing deployment of renewable sources (namely wind and solar photovoltaics, in addition to hydropower), improved energy efficiency (our "first fuel" since the cheapest and cleanest kWh is the one that is saved!), distributed storage, and the growth of electric mobility (replacing in large-scale internal combustion engine vehicles). The energy transition will be facilitated by the deployment of information technology and intelligent cyber-physical systems along the entire infrastructure and value chain from generation to consumption, adequate policy and regulatory frameworks and new market design and instruments empowering new players, such as consumers and aggregators. However, as the IEA (2020) points out, there is a "gap between expectations of fast, renewables-driven energy transitions and the reality of today's energy systems in which reliance on fossil fuels remains stubbornly high", which requires that energy decision makers (DM) need to take a hard, evidence-based look at the implications of the choices they make. Still, the increasing penetration of renewable sources comes with a price since they are inherently variable and, therefore, require more stable backup systems, generally based on fossil-fuel plants, to keep the reliability of supply, and a more proactive role of demand-side resources. Moreover, every technology uses natural resources and entails some form of environmental degradation, as pollution, over its entire life cycle from raw material extraction to disposal at the end of the useful life. The exploitation of abundant "clean fuels", as wind and sunlight, has environmental impacts that cannot be hidden looking just at the operation phase, which decision models should acknowledge.

Demand-side management refers to actions designed to optimize costs by controlling the amount and timing of energy consumption, possibly in response to time-differentiated tariffs reflecting generation availability and grid conditions. The aim is to make the integrated optimization of all energy resources (exchanges with the grid, loads, local generation, and storage including electric vehicles) to minimize the energy bill without jeopardizing comfort requirements (e.g., related to indoor or hot water temperature, state of charge of the electric vehicle battery, postponement in the operation of the laundry machine). These actions can be beneficial to the consumers (and prosumers, i.e., actors simultaneously producers and consumers of energy) by lowering bills, but also for retailers able to exploit variable wholesale prices and fixed retail prices over a given period for increasing profits, and grid operators able to make a more efficient network management reducing losses and improving reliability.

As several energy decisions may impact community's well-being (there are several examples of populations opposition the installation of "clean energy" wind farms), participatory MCDA approaches should be conducted offering a structured procedure to integrate the relevant stakeholder participation in the decision process

(Kowalski et al., 2009; McKenna et al., 2018). The role of participatory MCDA is particularly relevant in the establishment of energy communities, which have the potential to contribute to the energy transition by empowering consumers, increase the demand satisfied by renewable sources, and promote collaborative social transformation. In this setting, "renewable energy communities" and "citizens energy communities" were brought to the center of the European energy policy by the recast of the Renewable Energy Directive and the common rules for the Internal Electricity Market Directive (Reis et al., 2021). Energy communities can also be an important actor for the mitigation of energy poverty, in which MCDA approaches can assist to design policies and programs considering multiple vulnerability dimensions as heating burden, socio-economic, and building vulnerabilities (März, 2018).

This chapter aims to put in perspective the added value that MOO and MCDA models and methods can offer to support sound and sensible decisions in energy systems planning, which have challenging implications in multiple domains (with natural interplay with other SDG as water management, industrialization processes, smart cities) due to the pervasiveness of energy as a factor of prosperity. Since a review of applications of MOO and MCDA models and methods in problems in the energy sector would be impossible due to the vastness of literature (see Diakoulaki et al., 2005; Henggeler Antunes & Henriques, 2016; Kumar et al., 2017; Cui et al., 2017; Henggeler Antunes, 2019; Estévez et al., 2021; Sousa et al., 2021), this chapter focus mainly on the role that MOO and MCDA approaches can offer in providing the models and methodologies for sounder decisions in challenging problems associated with the SDG 7—*Ensure access to affordable, reliable, sustainable and modern energy for all*. Relevant energy planning problems are outlined evidencing the multiple, conflicting and incommensurate evaluation aspects that should be considered to produce sensible decisions that can be implemented, thus complying with the need for action underlying the SDG. Just for the sake of organization, MOO and MCDA approaches for energy planning, with focus on power systems, are addressed in different sections, with some attention paid to techniques to cope with uncertainty. The conclusions section sheds light on two urgent fields of intervention in which the MOO and MCDA approaches can have a role—the effects of the pandemic on energy planning and the combat to energy poverty at the light of SGD 7.

2 Multiobjective Approaches for Power Systems Planning

Power systems planning were the first type of problems addressed using MOO and then MCDA approaches, namely involving generation and transmission network expansion planning, often also considering technology choice and location issues (of new power plants or new lines). These problems are of strategic nature since they involve large investments for facilities that are expected to operate for several decades. Operational planning problems have typically a timeframe of months-years, including generation and transmission scheduling. Short-term planning refers to decisions to be made in hours or days, including unit commitment and optimal power flow.

2.1 Power Generation Planning

The power generation capacity expansion planning problem involves determining, for a given planning period, the amount of power to be installed of each generating technology, and the energy to be produced. The problem may involve a large number of discrete and continuous variables, depending on the discretization of the planning period and the technologies considered (e.g., coal, large scale and small hydro, combined cycle natural gas, nuclear, wind, geothermal, solar photovoltaic, etc.). In addition to conventional and renewable supply-side options, the consideration of demand-side management (DSM) options enlarges the planning portfolio, which may enable to avoid the operation of, in general very expensive and polluting, generation units just to supply short duration peaks. DSM is aimed at smoothing the load diagram (namely by peak clipping and valley filling), which can be implemented in practice by means of by direct load control or incentive mechanisms, being included in optimization models as an equivalent generation unit allowed to operate in demand peaks with a capacity limit.

Cost minimization models were used to deal with power generation capacity expansion planning until environmental issues began to be inescapable. Although the first models proposed recognized the multiobjective nature of the problem, the environmental concern was concealed in the economic objective function, in general by monetizing pollutant emissions or other impacts. Therefore, the tradeoffs between the economic and environmental dimensions could not be suitably unveiled, thus missing the value-added of a multiobjective approach even though the multiobjective concern may have existed at the outset. In MOO models, the objective functions commonly include the minimization of the total expansion cost that may also account for outage costs and losses, the minimization of pollutant emissions (CO_2, SO_2, $NO_{x,}$ particulate matter), the minimization of the investment in and operation of carbon capture technologies, the minimization of a proxy for environmental impacts (an economic indicator monetizing pollutant emissions or a volume indicator) that may consider radioactive wastes and a life-cycle perspective, the maximization of the system reliability/safety, the maximization of social impacts as employment at regional level/national level, the minimization of the external energy dependence of the country, the minimization of a set of risk indicators considering technical, portfolio investment, energy security associated with supply source diversification, and fuel price risks. The maximization of reliability is also taken into account by optimizing the preventive maintenance schedule of generating units for economical and reliable operation.

The constraints refer to issues as satisfaction of forecasted demand plus reserve margin, lower/upper bounds of generation capacity, budgetary limitations, technological and political restrictions (e.g., phasing-out nuclear power units), operational availability of generating units, rate of growth of the addition of new capacity, primary energy availability (e.g., biomass), transmission line restrictions in face of generation units location, coal/gas production and transportation capacities, need to account for multiple water uses in hydroelectric reservoirs, pumping capacities in pumped hydroelectric energy storage. The carbon abatement policy under the Clean Development Mechanism (CDM) within the European Union Greenhouse Gas Emission Trading Scheme is also considered in some models. Technical aspects as voltage profile (over/under) deviation, line and transformer overloading, short circuit capacity and harmonics are relevant, namely concerning renewable energy sources.

SDG 7 is closely linked to SDG 6 (*Ensure availability and sustainable management of water*) as hydroelectric systems, being the main controllable renewable resource due to the existence of large reservoirs, must account for multiple water uses. The energy uses require an optimized management of reservoir cascades in the same basin as well as the pumping of water from a lower to a higher elevation reservoir in pumped hydroelectric units to store excess energy in periods of low demand that can then be offered in periods of high demand or to account for low generation of intermittent (wind, solar) sources. Pumped storage is the largest capacity form of grid energy storage available worldwide and it plays a crucial role to balance the system when large shares of intermittent generation is being dispatched. Hydroelectric systems require balancing energy and non-energy uses, which may be incorporated in the models as objective functions or constraints, as dam safety, discharge and spill control, flood protection, agriculture irrigation, industrial and domestic water supply, navigation and recreation, dilution of pollutants and effluents capability, ecological sustainability and protection of species.

The models are typically multiple objective linear programming (MOLP) or mixed-integer linear programming (MOMILP) models, of large dimension namely when the analysis requires a fine-grain discretization of the planning period. To make the models tractable, nonlinear issues, for instance associated with reliability, are generally linearized, e.g., using dual reformulation or McCormick relaxation. Due to the vastness of the nondominated solution set, the algorithmic approaches do not aim, in general, to make an exhaustive computation of the nondominated front, in general using some type of scalarizing technique, but rather offering a characterization enabling to unveil the tradeoffs between the competing objective functions in different regions where solutions with different features are located. To avoid the computation burden with no impact on the enlightenment of the DM, interactive methods are often used exploiting the DM's preference information to guide the search for regions of interest aiming to find satisfactory compromise solutions. The dimension and the combinatorial nature of MOMILP models, for which the optimal solution to a scalarizing function cannot be obtained with a reasonable computational budget, led to the use of metaheuristics (MH) with the aim to expedite the computation of (approximate) nondominated solutions. Population-based MH (as genetic/evolutionary algorithms, particle swarm optimization, differential evolution) have been used, which hopefully make the solution population to evolve towards a good approximation of the nondominated front (which, in general, is unknown).

Multiobjective approaches to deal with power generation expansion planning models should be able to consider the several sources of uncertainty that are intrinsic to these problems. Those uncertainties include demand growth rates, load variation, primary energy prices, inflows to hydro reservoirs, wind speed and solar insolation, public attitude towards nuclear. Techniques to deal with uncertainty include stochastic, fuzzy, interval or robust programming. The aim is to find robust solutions, i.e., solutions that perform well for a plausible range of model coefficients variation.

Generation capacity expansion planning models, in the electricity and gas industries, should consider the market structures that replaced the traditional vertical organization in most countries. In this setting, profit and market share maximization objective functions are developed in the perspective of the private generation company competing in the wholesale market.

2.2 Unit Commitment and Dispatch Planning

The unit commitment problem consists of scheduling generating units of multiple conventional and renewable technologies to be on, off, or in stand-by (reserve) mode, in a planning period, to meet demand. When the system is vertically integrated, unit commitment is carried out in a centralized manner, with the objective function of minimizing overall costs subject to demand and reserve margins requirements. When the generation segment is competitive, the generation company makes the unit commitment plan to maximize profit considering estimates of the volume of energy to be sold in the wholesale markets and through bilateral contracts. Economic dispatch involves determining the optimal combination of power output of online generating power plants to minimize the total fuel cost satisfying load demand and operational constraints. Since load demand can have short-term variations, dispatch should be able to adapt guaranteeing adequate cost or profit levels, considering technical issues as voltage control, congestion, transmission losses, line overloading, voltage profile. The market structures influence the model perspective; rather than maximizing profits, an independent system operator aims to maximize social welfare.

The objective functions in economic-environmental dispatch are the minimization of cost, maximization of profit, minimization of fossil-fuel power plant (NOx, SOx, CO_2, PM) emissions, minimization of the variance of active and reactive power generation mismatch, minimization of voltage deviation to avoid violation of active power line flow limits, minimization of dispatchable dispersed generation production deviations with respect to the set points calculated by the day-ahead scheduler, minimization of network losses, maximization of operational efficiency, maximization of system reliability level. The constraints refer to power balance (total power satisfying demand plus transmission losses), generation capacity and transmission line loading limits, spinning reserve requirements, ramp rates, security limits, emissions, supply of ancillary services, capacity limits, operation levels, minimum up/down time, maximum up/down ramping rate.

Microgrids are a key trend in the energy transition, as small-scale, self-sustaining power networks, offering further reliability and resilience, comprising multiple generation sources, diversified loads including electric vehicles, and energy storage systems. Microgrids can operate connected to the main grid, allowing for mutually favorable power exchanges, and in islanded mode, namely in disturbance conditions or when local generation surplus exist. MOO models for the control of microgrids consider objective functions of economic, environmental and technical nature, as minimizing the investment, operation and maintenance costs, minimizing losses, minimizing pollutant emissions, minimizing energy not supplied in both connected and islanded modes, minimizing the voltage deviation from its nominal value at grid nodes, minimizing the cost of the energy imported from the upstream grid, maximizing the security margin, maximizing the provision of services to the main grid, minimizing the energy level required for emergency demand response programs at interconnections, maximizing the overall utility. Some of these aspects (e.g., losses, environmental impacts, load not served) may be monetized and incorporated in an overall cost objective function. Constraints deal with power balance, power generation capacity of renewable and non-renewable sources, storage limits as well as charge/discharge rates, spinning reserve requirements, and voltage drop at network buses.

2.3 Network Planning

A well-dimensioned network infrastructure, consisting of overhead and underground transmission and distribution lines and substations to step up/down voltage, is essential to deliver energy from generation units to consumers. Due to the sector unbundling in several countries, transmission and distribution network activities have been separated from generation and retail activities and are under regulatory determinations, including the approval of investment plans, quality of service requirements and remuneration allowed. This separation of activities, although motivated by economic efficiency gains, may lead to sub-optimal decisions from a societal perspective (e.g., investment in new generation to supply further demand may be hampered by low investment rates in the necessary grid connections). The networks' natural monopoly characteristics also require that regulators set transparent access mechanisms, including the definition of fair network access rates at different voltage levels. The evolution to smart grids, using information and communication technologies and distributed computational intelligence, offering bi-directional communication between grid operators and end-users, and accommodating larger shares of dispersed generation, raises new challenges for distribution network planning considering supply and demand resources. Dispersed renewable generation connected to the distribution network and new relevant loads as electric vehicles impose additional planning challenges, namely regarding technical requirements with implications on the economic dimension.

The aim of network operators, which may own or just manage the assets through concessions (e.g., from municipalities), is offering efficient, reliable and nondiscriminatory service by means of adequate planning of infrastructure expansion, technological modernization and reliable operation. Objective functions in MOO network planning models encompass economic, environmental, technical and quality of service aspects, including infrastructure (substations and feeders) construction/reinforcement costs, equipment (transformers, protection devices, etc.) installation/upgrade costs, overload costs, energy losses costs, regional/national economic growth induced by projects, value of facilitating competitive wholesale markets, environmental impacts of line corridors (e.g. through forests or protected land, including offering grid connection points to dispersed renewable generation), health damage due to population exposure to electromagnetic fields, compliance with safety standards associated with thermal, voltage and stability requirements, voltage and frequency deviation, system/customer average interruption frequency and duration indices. Constraints refer to network characteristics (e.g., radial structure), demand satisfaction, power flow equations, capacity limits in transformers and feeders, upper/lower limits for node voltages, and interruption duration.

2.4 Demand-Side Management

Demand-side management programs have been used by utilities to achieve cost reduction and operational benefits, as reducing peak demand, increasing load factor, and reducing losses. The aim is to exploit the flexibility end-users generally have in load operation timing to modulate demand according to time-differentiated prices, generation availability and grid conditions, i.e., adopting a load follows supply management paradigm. DSM actions entail changes on the regular working cycles of loads, minimizing the discomfort caused to the consumers. The load operation can be controlled by the utility through direct load control or involve voluntary load shedding, shifting the habitual operation cycles to other periods or changing operation settings (as thermostat setpoints). DSM gained an increased importance due to the penetration growth of intermittent renewable sources in the generation mix, which may produce wholesale electricity prices volatility and reliability concerns (generation deficit and network congestion). Loads that provide energy services whose quality is not substantially affected by short duration supply interruptions (for instance, thermostatic loads such as electric water heaters and air conditioners in the residential sector) are adequate targets for demand-side actions, which should be designed considering multiple objectives of different nature (economic, technical, comfort, quality of service). In a unbundled energy sector, DSM offers potential gains to multiple players in the value chain: consumers can minimize costs without jeopardizing comfort making the most of time-of-use tariff schemes; retailers can maximize profits in face of volatile wholesale prices and retail prices fixed in a certain period; distribution system operators are interested in decreasing transformer and line overloads to improve reliability and reduce losses thus avoiding/postponing investments in equipment reinforcing; generators can avoid the operation of power plants with higher variable costs and higher emissions thus decreasing energy marginal prices and environmental impacts.

The models to optimize the utilization of demand-side resources, also including local microgeneration (photovoltaic panels) and storage systems (a static battery or an electric vehicle able to deliver the energy stored in the battery when parked), generally consider cost, quality of service and technical objective functions. The cost objective function refers to energy and power (penalizing peaks) costs and may include a revenue term from selling back energy to the grid. If allowed by the regulatory framework, the surplus of energy locally produced, or the energy stored in the battery can be sold to the grid according to some remuneration scheme. The quality of service objective function can be modeled by means of a penalty coefficient for rescheduling loads outside the most preferred periods, thermal comfort measured by the deviation of the indoor temperature or the hot water temperature with respect to a reference temperature, postponement in the completion of a certain service (e.g., laundry, dishwashing), maximum continuous time interval that a state variable (e.g., temperature) is over/under a prespecified threshold, minimizing the frequency of operation interruptions imposed on loads. In some models, the comfort is modeled by means of a utility function associated with the energy services delivered by the controlled loads, which is less realistic (since utility functions are difficult to elicit and are often associated with the amount of energy consumed, which is counterproductive) than modeling the actual physical appliance operation.

The consumer's flexibility in load operation can be exploited by aggregators, an emerging middleware entity able to gather end-user's resources to respond to grid requests in periods of grid congestion or generation deficit, which may involve temporarily decreasing or increasing consumption. Electric vehicles, air conditioning systems and electric water heaters are the loads most used for this purpose, due to their relevant consumption and utilization flexibility degree.

2.5 Energy-Economy-Environment Planning Models

The analysis of policies to analyze the interactions between the economic system (at national or regional levels), the energy sector, and their impacts on the environment requires the simultaneous consideration of these multiple axes of evaluation in the models. Input-output analysis (IOA) and general equilibrium models (GEM) are often used as frameworks to develop MOO models. IOA represents the interactions between the whole economy, which is divided into sectors, and the energy system, enabling to compute the energy consumed for the provision of goods and services to the economy and quantify the corresponding pollutant emissions. GEM encompass interrelated markets and represent the (sub-)systems (energy, environment, economy) and the dynamic mechanisms of the agents' behavior to compute the competitive market equilibrium and determine the optimal balance for energy demand/supply and emissions/abatement.

Models are typically MOLP, considering objective functions as maximization of the gross domestic product, private consumption, employment level, self-production of electricity, electricity generation based on renewable sources, and minimization of the CO_2 emissions, global warming potential, acidification potential, wastes, coal utilization, energy imports. Constraints include inter-temporal inter-industry constraints, water resource limits, labor available for each industry and industrial expansion limits, balance of payments equilibrium, production capacity, exports and imports bounds, public deficit limits, storage capacity and security stocks for hydrocarbons, pollutant emissions, energy and carbon intensity.

3 Multicriteria (Discrete Alternative) Energy Planning Models

Some energy planning problems are less prone to the development of optimization models, but they can be modeled as multicriteria problems considering a discrete set of alternatives to be evaluated by a consistent set of criteria. The explicit definition of alternatives and criteria generally requires a careful problem structuring phase, including the participation of the stakeholders. Participatory approaches enable supporting interactive planning and learning, helping the stakeholders to systematically consider, articulate and apply value judgments, contributing to the acceptance of decisions that must establish balances between economic, environmental, social and quality of service aspects.

The energy planning problems generally addressed by MCDA approaches comprise the comparison of energy supply systems including renewable and conventional technologies, evaluation of national/regional energy plans and policies (e.g., design of renewable energy or carbon capture and storage promotion policies), selection of energy projects (e.g., involving investment options in wind, solar PV, bioenergy, geothermal, hydrogen), equipment location decisions (e.g., of wind farms and hydro and thermal power plants causing different types of impacts, possibly assisted by geographical information systems), evaluation of energy efficiency actions (e.g., sorting initiatives promoted by utilities, with or without public funds authorized by a regulator), etc.

The criteria address mainly economic, environmental, technical and social issues associated with energy decisions in several contexts.

Technical criteria include: adaptability—the potential of a technology to be adapted to specific conditions; availability—whether the energy resource is readily available in terms of time or load factor, which is more relevant in renewables; continuity and predictability—the ability to keep stable the energy generated without being affected by external factors; diversity of technologies or supply sources—to favor diversified portfolios and reduce risks; efficiency—ratio between the useful energy that can be obtained from the input of a given source; feasibility—usually associated with the confidence in the implementation of an energy policy; local technical know-how—complexity of the technology vs. the capacity of ensuring an adequate support for its installation and maintenance; technology maturity—technology consolidation degree, which may be assessed by its penetration worldwide; peak load response—ability to respond promptly to variations in demand; production capacity—availability of a fuel as a feedstock for existing or new generation capacity; reliability—the capacity of a device/system to perform as designed, the resistance to failure, the ability to perform a required function under stated conditions for a specified period of time, or the ability of failure without catastrophic consequences; risk—normally associated with the implementation of an energy policy or occurrence of a major disaster; security—of the supply system, namely related to the reduction of energy dependence or fuel imports in face of factors that may affect the continuous availability of non-renewable primary energy from their origin. Specific technical criteria may be identified for particular studies, for instance the infrastructure necessary for deploying hydrogen fueling systems for transportation, the temperature and solar capacity factor for the assessment of concentrated solar thermal technologies, or the effectiveness for the assessment of pollution abatement measures.

Economic criteria include: externality costs—imposed on society and environment but not accounted for by the producers and consumers, and therefore generally not included in market prices; fuel cost—provision of raw materials necessary for the operation of the energy supply system (e.g. coal or natural gas for conventional thermal plants or uranium for nuclear power plants), which may be influenced by political instabilities; infrastructure costs—also comprising grid connections; investment cost—for the purchase of equipment, installations building, construction of roads and connections to the main grid, engineering services; maintenance costs—fixed and variable costs for preventive and corrective maintenance works; production costs—indicating how competitive the system is compared with other production technologies; economic impact—capacity of the energy project or policy of promoting local/regional/national economic development; economic viability—assessed using indicators as net present value, internal rate of return, cost-benefit analysis, payback period, useful life. Other specific economic criteria may consider availability of funds, compatibility with the national energy policy objectives, political acceptance, geopolitical issues, legal framework, commercial aspects, market size, energy price stability, etc.

Environmental criteria may be broadly divided in local and global impacts. Local impacts include: acidification and eutrophication—the acidification potential and the contribution of the deposition of nitrogen-containing compounds to eutrophication of terrestrial and marine ecosystems; methane emissions—released mainly during biomass burning depending on the efficiency of the burning method; CO_2 emissions—considering a direct contribution for the increase associated with fuel combustion or the reduction associated with renewables, including the computation of emissions based on lifecycle assessment; effects on natural environment—the potential risk to ecosystems caused by energy policies and strategies due to impacts on air, water and soil quality, human toxicity as well as fresh water, marine and terrestrial eco-toxicity; land use—required by power plants since different energy systems may have different land use impacts for the same output level; local pollutants—emissions of pollutants with local and regional impacts as non-methane volatile organic compounds, ash emission and carbon monoxide, smell, etc.; noise—caused in neighbor areas by new infrastructures as wind parks; NO_x emissions—contribute to air pollution, acid deposition and climate change; particulate matter (PM)—the primary cause for the rise of mortality and morbidity in the vicinity of power plants, whose risk for human health depends on size, distribution, microstructure and chemical composition of particulates released into the atmosphere; radioactivity—small amounts of radioactivity are released to the atmosphere from coal-fired and nuclear power stations, and nuclear power stations and reprocessing plants also release small quantities of radioactive gases; SO_2 and SO_x emissions—sulfur emissions into the atmosphere in the form of SO_2 and SO_3 derive from the burning of fossil fuels or even wood and are contributors to acidification and responsible for damage to human health and ecosystems; visual impact—the visual nuisance that may be created by the construction of a wind turbine or a new power plants upon the landscape; wastes—direct damages on the environment due to disposal and costs associated with waste treatments.

Global impacts include: climate change/global warming potential/greenhouse gas (GHG) emissions—GHG emissions or global carbon footprint; resource depletion—cumulated energy input and material input throughout the project or energy policy lifetime; sustainability of energy resource—measure of supply availability over a long period of time, favoring renewable resources.

The social criteria comprise distinct types of impacts, including health impacts, risks, development potential and acceptability. Health impacts—human health hazards due to the energy sources can be compared using the concept of expected years-of-life lost; food safety risk—assesses the risks of utilizing bio-fuels on food supply safety, which is relevant as the increased use of biofuels in transportation may cause increase of food prices; safety—the risk of fatal accidents or injuries in construction and operation phases; job creation—impacts on direct, indirect or induced employment, either with local or national implications; regional development—progress induced in the less developed regions of a country by the implementation of new technologies or energy plans; social impacts—effects on the community due to the implementation of the energy project; acceptability to the user—considering attributes as usability, reliability, efficiency of use and comfort; social acceptability—considering the consensus among social partners, as the opinion of the population and pressure groups may influence the completion of the project. Other study-specific social criteria include human resources dedicated to research and development activities, share of household income spent on fuel and electricity, cultural heritage protection, educational supportive actions to increase energy environmental awareness.

A vast array of MCDA methods has been used to deal with energy planning problems, including value/utility theory, outranking and AHP/ANP approaches. Simple Additive Weighting has been used generally to derive sustainability global indicators, unfortunately without caring of their applicability conditions in face of the actual problem namely in the conversion of qualitative scales into quantitative ones to perform aggregation. Multiple Attribute Utility Theory (MAUT) has been mostly used in energy efficiency studies to capture the uncertainty associated with the outcomes of alternatives, allowing to represent the DM's preferences as multiple attribute utility functions. The Multiple Attribute Value Theory (MAVT), which may be perceived as MAUT with no uncertainty in the consequences of the alternatives, has been mainly used in power generation technology comparisons, in particular to rank power expansion alternatives or to prioritize investment portfolios in capacity expansion and energy security. The Ordered Weighted Average (OWA), which can combine non-weighted and weighted linguistic information, has been used in the formulation of sustainable technological energy priorities.

The outranking approaches, including several versions of ELECTRE (Elimination and Choice Translating Reality) and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), have been regularly used to deal with energy planning problems. ELECTRE III has been mainly used in energy plans and policies studies for the ranking of renewable energy resources. ELECTRE TRI, which assigns alternatives to predefined ordered categories of merit, has been used for the assessment of agricultural biogas plants, the definition of national priorities for GHG emissions reduction, the selection of wind energy projects, the appraisal of energy-efficiency initiatives. PROMETHEE has been mainly used in energy plans and policies concerning the design of renewable energy policies and the comparison of power generation technologies. PROMETHEE II for performing a complete ranking of all alternatives has been used in the evaluation of sustainable technologies for electricity generation and assessment of renewable energy projects. AHP has been used in combination with other methods, using the pairwise comparisons of AHP to derive the weights that are then used in the operational framework of other methods (e.g., TOPSIS or VIKOR). Some of these approaches do not pay the necessary attention to the meaning of weights, which is different in distinct methods, and consequently the results sometimes lack the necessary methodological consistency. The problems addressed range from the evaluation of conventional and renewable energy sources for space heating in the household sector, assessing energy policies, choosing optimal locations for thermal power plants, and environmental performance of urban energy use plans. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), NAIADE (Novel Approach to Imprecise Assessment and Decision Environment), VIKOR (Multicriteria Optimization and Compromise Solution) and MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) are other methods generally used in energy planning problems, encompassing technology selection, location decisions, assessing policy measures for residential heating energy and domestic electricity consumption, comparing small scale and large scale approaches to renewable energy provision to help meet targets at the lowest social, economic and environmental costs. Please see the review by Henggeler Antunes and Henriques (2016) for references.

Due to the social relevance of most problems, participatory MCDA has been used to consider the complexity of socio-economic and biophysical systems characterized by multiple and conflicting interests, analysis perspectives and uncertainty, enabling to reconcile the incommensurate valuation of the long-term nature of sustainable development associated with energy systems (McKenna et al., 2018).

Multiple sources of uncertainty are at stake in MCDA energy planning studies, from those associated with data (absence, inconsistency, inaccuracy) to the very nature of expression of the DM's judgments. The difficulty of providing exact numerical values for the criteria, making precise evaluations and translating human reasoning into a qualitative/quantitative scale has been largely recognized (Doukas, 2013). Dealing with these distinct forms of uncertainty is needed to reach recommendations that can be trusted. Sensitivity analysis assesses the variations in the input information (data, preference expressing parameters, etc.) and additional assumptions. Different forms of sensitivity analysis are combined with the MCDA methods mentioned above. In most applications, sensitivity analysis is based on a "one at time" approach by considering changes in the results due to variations in a single parameter. Sensitivity analysis is generally performed by varying a single parameter, such as considering different sets of criterion weights accommodating different perspectives, pessimistic/optimistic scores for each alternative in some criteria, preference/indifference/veto thresholds. Stochastic distributions, e.g., for the weights, are mostly used in the framework of value and utility theory approaches. Fuzzy sets have been used to simultaneously handling numerical data and linguistic knowledge expression. In scenario-based analysis, a number of possibly "states of the world", hopefully mutually exclusive and collectively exhaustive, is constructed to analyze new projects, being often associated with outranking methods. Robustness analysis is generally associated with the min-max regret criterion to derive stability intervals for weights, i.e., the range of weights that give the same recommendation, either interpreting the weights as tradeoff ratios (as in MAUT) or as the voting power of criteria (as in outranking approaches).

4 Conclusions and Challenges Ahead

The energy sector is essential for the satisfaction of societal needs, being at the heart of most activities that shape our lives in modern societies. Driven by higher energy demand in the years just before the pandemic, global energy-related CO_2 emissions rose in 2019 to a historic high of 33.1 Gt CO_2, the power sector accounting for nearly two-thirds of emissions growth. As stated by the IEA (2020), notwithstanding the drop in 2020, global energy-related CO_2 emissions still reached 31.5 Gt, with CO_2 attaining its highest ever average annual concentration in the atmosphere of 412.5 parts per million in 2020, that is 50% higher than the early years of the industrial revolution. Global energy-related CO_2 emissions are projected to rebound in 2021, growing by an estimated 4.8% as demand for coal, oil and gas recovers with the economy. The importance of "ensuring access to affordable, reliable, sustainable and modern energy for all", recognized in Sustainable Development Goal 7, is central to the fulfillment of the 2030 United Nations Agenda for Sustainable Development.

The energy transition embodying the decarbonization of the energy sector and the economy as a whole is the all-embracing challenge of our generation.

Planning models to deal with problems in the energy sector, ranging from strategic long-term to operational short-term, should encompass the multiple, conflicting and incommensurate aspects of evaluation of the merits of distinct courses of action pertaining to economic, environmental, social, quality of service and technical issues. MOO and MCDA models not just capture in a more realistic manner the complexity and the manifold interactions at stake in energy planning problems, but also offer a value-added in exploring a variety of possible decisions representing different tradeoffs between the competing evaluation aspects, thus enabling a more thorough analysis of potential solutions. MOO and MCDA methods include in the decision process the stakeholders' perspectives and preferences, thus facilitating solution acceptance and implementation.

The energy sector will remain one of the most active and exciting areas of application of MOO/MCDA models and methods, with an enriching cross-fertilization between challenging problems and methodological innovation. In turn, MOO/MCDA models and methods can offer supporting sound and sensible decisions having energy systems at the heart, with stimulating implications in multiple domains due to the pervasiveness of energy as a factor of prosperity.

Last but not the least, two important issues will deserve further attention in the short-term for which MOO and MCDA models can be of help—the effect of the Covid-19 pandemic and energy poverty. Studies need to be carried out to ascertain the favorable or setback impacts of the pandemic on the energy transition. According to the International Energy Agency (IEA, 2020), global energy demand is expected to have decreased by 5% in 2020, with global electricity demand falling just 2%. Regarding fossil fuels, the IEA estimates indicate a drop in energy-related 8% in oil, 7% in coal, and 3% in natural gas demand, with a slight rise in the contribution of renewables. The energy-related CO_2 emissions declined by 7%, to the levels of a decade ago. But, as the IEA points out, low economic growth is not a low-emissions strategy, and only continuing structural changes in production and consumption patterns can curb emissions in the aftermath of the pandemic. We cannot afford the economy recovery to be more of the same.

Even in industrialized societies, energy poverty is a relevant problem created by low earning levels, unaffordable energy prices, and energy needs due to housing deficiencies as poor insulation. These factors interact and have feedback between them that aggravates the problem, particularly in very cold climates. Therefore, programs should be designed to alleviate energy poverty balancing economic and social objectives, particularly using the recovery and resilience programs being implemented to counteract the effects of the pandemic. As the SDG 7 clearly enunciates, 759 million people lack access to electricity, 3 out of 4 of them living in sub-Saharan Africa. MOO and MCDA have the tool bag of models and methods to assist supporting better decision to make the most rational use of the resources available to foster prosperity, for which ensuring access to affordable, reliable, sustainable and modern energy for all is a key desideratum.

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Stakeholder Engagement and ANP Best Research Practices in Sustainable Territorial and Urban Strategic Planning

Hannia Gonzalez-Urango, Enrique Mu, and Mónica García-Melón

Abstract Strategic planning of sustainable territorial urban development (STUD) is usually carried out on the basis of a participatory decision-making process that focuses on important, sometimes conflicting issues and their impact on stakeholders. For this reason, ANP is particularly well suited for this purpose since it makes it easier for stakeholders to participate in the decision-making process as a group with minimum knowledge of the MCDM process. This study explores the use of ANP in sustainable development and in particular in territorial urban planning (STUD) and, more importantly, examines whether the method is being properly used in terms of its participatory decision-making and stakeholder engagement potential. Also, this research investigates if current ANP studies are reported in a way that allows the assessment of their validity and provides suggestions to address the identified gaps. For this purpose, the extent of the proper use of ANP in STUD applications in terms of (1) stakeholder engagement and (2) best ANP research practices, will be systematically reviewed in this paper in order to obtain a list of recommendations to optimize the use of ANP in STUD studies.

Keywords ANP · Sustainable development · Urban local development · Territorial local development · ANP best practices · Sustainable territorial and urban development STUD

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1 Introduction

ANP is a multicriteria decision-making methodology developed by Saaty (2001) and which allows for complex, interdependent and feedback relationships between the elements in a problem (Sipahi & Timor, 2010). Following its introduction (Saaty, 1996) it has been used in many different multi-disciplinary applications (Chen et al., 2019a).

At the same time, sustainable development SD, although a widely used phrase and idea, has many different meanings and provokes many different responses (Hopwood et al., 2005). It is a multidimensional concept that implies diverse perspectives and leads to issues that are characterized by a high degree of conflict (Boyko et al., 2006). Nowadays sustainability seems to have permeated every sphere of society. It is a trendy topic that attracts the interest of academics and practitioners in different areas.

While we will provide a more formal definition later in the chapter SD can be considered to be a complex matter that must integrate different levels of action and decisions, including conflicting perspectives. The achievement of appropriate arrangements becomes difficult when the intervention of different agents, objectives and factors and the interaction of complex elements in complex contexts are considered. The correct implementation of the SD approach includes a multidisciplinary perspective and implies multiple decision problems. Decisions regarding SD imply socio-economic, ecological, technical and ethical perspectives and have to take into account a large number of variables, of both a qualitative and quantitative nature, involving multiple fields and applications. To deal with these kinds of issues multicriteria analysis tools are very useful (Bottero & Mondini, 2008).

The multicriteria approach is adequate to deal with sustainability issues at both micro and macro levels, and the use of a multicriteria framework is a very useful tool to implement an interdisciplinary approach (Bottero & Ferretti, 2010a). Many authors introduced the use of MCDM techniques for sustainability issues (Ginevičius & Podvezko, 2009). Many of them focus on the use of the Analytic Hierarchy Process (AHP), which has stood out as the most often used (Dos Santos et al., 2019). Some others use ANP, a more evolved technique than AHP which allows us to analyze the dependences and influences among criteria, something not possible in the strict hierarchy of criteria proposed by AHP.

ANP is particularly suited for sustainable development planning since SD deals with complex interactions among different components of real systems, such as sustainability. It facilitates participative solutions and the integration of stakeholders' judgments and perspectives.

The research objectives of the present study are to survey the extent of ANP use for SD and in particular for territorial/urban studies. More importantly, this chapter also explores if ANP is properly used to take advantage of its capabilities to facilitate stakeholders' engagement as well as according to current best ANP research practices. A final, key contribution will be providing recommendations toward optimizing ANP use in the context of strategic planning of sustainable territorial and urban development (STUD).

2 Theoretical Background: Literature Review

A systematic literature review will be performed to assess the extent and nature of ANP use in the sustainable development literature. Next, the specific STUD applications will be identified to allow for a more specific analysis of their extent of stakeholder engagement and use of ANP best practices.

2.1 Sustainability and Sustainable Development

The idea of sustainability originated in the context of renewable resources and was subsequently adopted as a broad slogan by the environmental movement (Lélé, 1991). Nowadays, the sustainability issue has become increasingly important, so much so that a new field of sustainability science is emerging. Sustainability science seeks the fundamental character of interactions between nature and society (Kates et al., 2001) involving a wide variety of disciplines and sectors. Hence, there are many definitions and approaches to address it, combining a diversity of knowledge and actors at different levels, and raising multiple questions and challenges.

Both terms, sustainability and sustainable development SD, are essentially represented, classified or expressed as an integration of these three dimensions or categories: (1) environmental/ecological, (2) social/sociocultural, and (3) economic (Fig. 1), known as the pillars of SD. This concept is often represented as three interconnected and mutually reinforcing rings (A), but can also be presented as the economy embedded in society and in the environment (B), or where interconnected social and economic systems are embedded in the environment (C) (Wentworth,

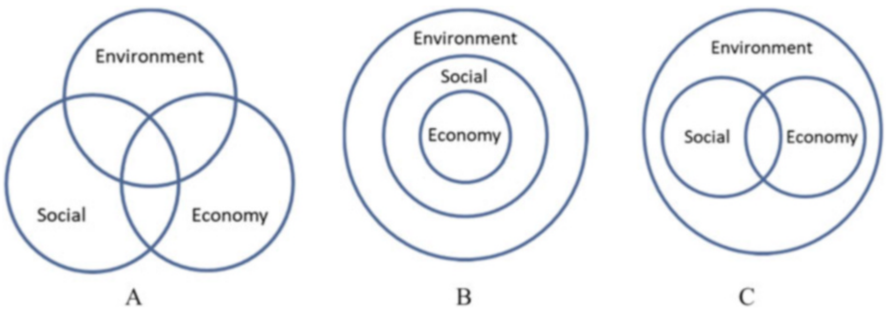

Fig. 1 Three visions of sustainable development dimensions. (**a**) Three-rings. (**b**) Nested. (**c**) Environmentally dependent. Adapted from: Watson (2018), Wentworth (2012)

2012; Watson, 2018; Goodland, 1995). Although the literature is awash with many different definitions and interpretations of SD (Mensah, 2019), so these dimensions can be modified in order to enhance one or other dimension.

Today SD is a worldwide issue. The proposed *2030 Agenda for sustainable development* adopted by all United Nations Member States in 2015 considers the same Brundtland definition. All the emerging concepts and policies around SD are related to intergenerational equity and balance, long-term risks and linking local actions to global concerns.

There are many works in all these three directions, at different levels and in multiple application areas. The concept of SD has also been embraced in several fields, each one adopting and adapting the term to its operations. There seems to be a need to transform the general concern regarding SD into specific targets at all levels, e.g.:

– Public policy: SD has become a highly visible idea in public policy debates. The main challenge for policy-makers is how to bridge the gap between theory and practice (Berke & Conroy, 2000).
– Planning: SD has been promoted as a new planning agenda. Efforts focused on transforming the concept into planning practices are emerging (United Nations General Assembly, 2015).
– Assessment: assessment approaches can support all levels of decision-making and policy processes. Indicators and composite indexes are increasingly recognized as useful tools for policy making and public communication. Numerous initiatives are being worked on that have developed quantitative indicators, metrics and frameworks. They have provided an evaluation from global to local systems, in short and long-term perspectives (Parris & Kates, 2003; Singh & Kotzé, 2003).
– Participatory process: SD in practice implies multiple negotiations to address multiple purposes of competing interest groups. Many definitions of SD include statements about open and democratic decision-making (Kates et al. 2001, 2005).

In summary, we can formally define SD as the framework, process, or group of processes for integrating environmental, social and economic elements to seek the long-term maintenance and enhancement of human well-being, which implies decisions at different levels. This study focuses on the analysis of texts that conceive of sustainability in this framework.

2.2 Stakeholder Engagement

Since the stakeholder concept emerged in the 80s it has rapidly spread through different areas (Freeman et al., 2010). Strategic planning of sustainable territorial and urban development (STUD) must include clear terms of coordination and cooperation among many different types of organizations or stakeholder groups (Iglesias-Campos et al., 2015; Sierra-Correa & Cantera Kintz, 2015; Kisman & Tasar, 2014).

A participatory approach involves the inclusion of different stakeholders so that their views, concerns and issues can be included in the planning process (UN-HABITAT, 2005). Hence, incorporating a participatory approach implies considering how to engage stakeholders in decision-making processes (Wolfslehner & Vacik, 2011). It is widely recognized that stakeholder engagement can lead to improved decision-making. However, decision makers must identify and engage appropriate stakeholder groups. This can be challenging when there is a wide and diverse range of potential stakeholders (Sharpe et al., 2021).

The participation of stakeholders in STUD is a real problem that has not been fully resolved. There are different applications to engage the participation of stakeholders in specific problems at organizational, industrial or political level, although, in STUD it is not always clear how they are included or selected, nor the level of inclusion.

According to stakeholder theory some approaches to address the analysis and inclusion of stakeholder can be identified. A stakeholder analysis is a useful method to identify who should participate in stakeholder engagement activities. However, the levels of engagement should also be considered.

Reed et al. (2009) reviewed stakeholder analysis methods in natural resources management and developed a typology categorizing methods for: identifying; categorizing and exploring relationships among stakeholders. Meanwhile, the Stakeholder Circle® methodology considers five steps to put stakeholders on the 'project management radar' (Bourne, 2020; Bourne & Weaver, 2010): identify, prioritize, visualize, engage and monitor. Finally, Sharpe (Sharpe et al., 2021) affirms that stakeholder engagement often follows a sequence of define, identify, then engage.

Thus, in terms of decision-making processes we can adapt the previous proposals in four types of analysis in order to engage stakeholders in STUD:

1. Stakeholder identification: Developing a list of those who may affect or be affected by planning processes could be considered a basic level of analysis in STUD studies. Techniques and methods used to identify stakeholders range from simple exercises to more time structured, intensive and in-depth approaches. They consist of determining who should be included in a decision-making process as a stakeholder (Varvasovszky & Brugha, 2000; Brugha & Varvasovszky, 2000; Prell et al., 2009; Saint Ville et al., 2017; Mu & Stern, 2012).
2. Stakeholder prioritization: There are a great deal of techniques for sorting stakeholders and establishing some classification in terms of: power vs. interest (Eden & Ackermann, 1998); power, urgency and legitimacy (Mitchell et al., 1997); links and relationships (Bryson, 2004; Biggs & Matsaert, 1999; Wasserman & Faust, 2007); proximity (Driscoll & Starik, 2004), level of stakeholder support (Rawlins, 2006), or access to resources (Eesley & Lenox, 2006). These techniques may bring an approach to determine a classification/salience for the role of actors in a decision-making process engaged in making decisions (Reed et al., 2009). Sometimes after a prioritization a categorization is often used to determine

how best to engage and manage stakeholder relationships or how stakeholders can better work together (Sharpe et al., 2021; Reed et al., 2009).

3. Stakeholder perspective: Considering stakeholders' points of view means understanding the interests and priorities of stakeholders and taking them into account when solving problems and decision-making. Joining their interest or demands may be done including the vision of some representative, using other techniques such as a survey, Delphi method or a focus group in a certain phase of the planning process (Hage & Leroy, 2008).
4. Stakeholder participation: Beyond identified or classified stakeholders or understanding their stake. The ideal goal of stakeholder engagement would be the effective inclusion of stakeholders in decision-making processes. Involving broader groups of stakeholders is important as they can contribute valuable knowledge that complements scientific expertise, enriching the knowledge base (Sharpe et al., 2021). This is relevant since in MCDM processes individual participation does have an influence on the result.

The expansive definition of stakeholders/interested parties/"the public"/actors also explains the wide ways of engaging them. No matter what kind of techniques or levels of engagement are selected. Many authors coincide on proposing that to have a clear process in mind would be of value for decision-making in STUD.

2.3 The Analytic Network Process ANP and Best Research Practices

The Analytic Network Process ANP procedure, developed by Saaty (1996, 2001), is a well-known Multicriteria Decision Method (MCDM), which provides a framework to address decision-making or problem assessment. It defines the prioritization model as a network composed of different elements (e.g. criteria, indicators, alternatives), grouped into clusters and connected to each other. ANP allows for complex, interdependent and feedback relationships among the elements in a problem (Sipahi & Timor, 2010).

The method was developed by Saaty (2001) to generalize his original Analytic Hierarchy Process AHP (Saaty, 1990). AHP defines the prioritization model as a hierarchy with independent assumptions on upper levels from lower levels. ANP is a more evolved technique than AHP (Fig. 2). Because many decision-making problems involve the interaction of several factors, they cannot be structured hierarchically, since factors at a high level depend on factors at a low level. Therefore, while the AHP represents a framework with a unidirectional hierarchical relationship, the ANP replace hierarchies with networks in which the relationships among decision levels and attributes are not easily represented as major or minor, dominant or subordinate, direct or indirect. Therefore, the importance of the criteria determines the importance of the alternatives, but in addition the importance of the alternatives

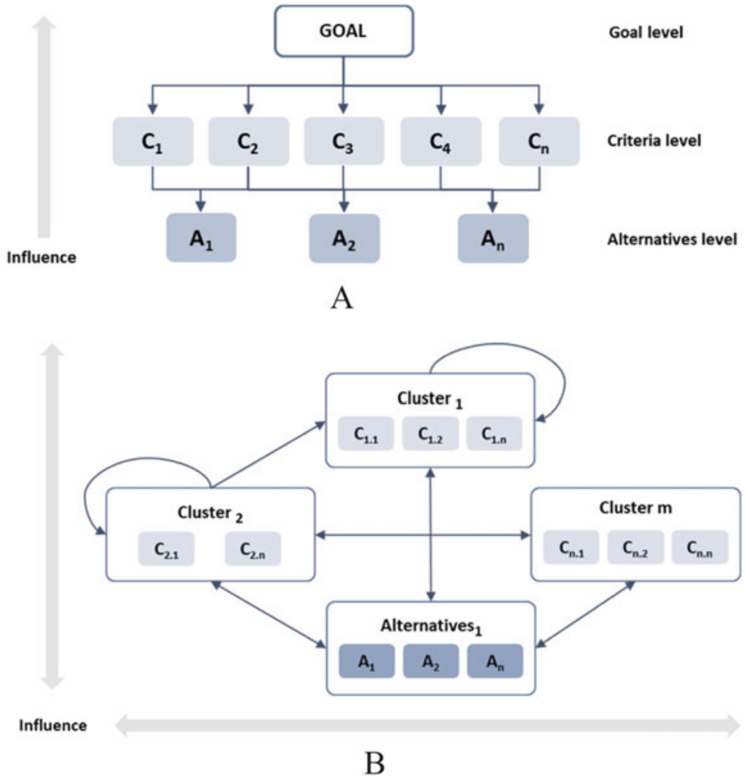

Fig. 2 Structural difference between AHP and ANP. (**a**) Basic AHP Hierarchy. (**b**) Basic ANP Network

can also have an impact on the importance of the criteria (Yüksel & Dagdeviren, 2007; Hsu & Hu, 2009; Boateng et al., 2015).

The ANP method is used to derive relative priority scales of absolute numbers from individual judgments (or from actual measurements normalized to a relative form) that also belong to a fundamental scale of absolute numbers (Saaty, 2005). Elements are evaluated via pairwise comparisons between pairs of elements to obtain their weights of importance. There are two possible structures for ANP: (Saaty, 2001) The 'simple' network of clusters and elements and (Sipahi & Timor, 2010) The 'complex' or BOCR network, which structures the problem by classifying elements into positive (benefits and opportunities) and negatives (costs and risks) categories. Detailed descriptions of the method can be found in Saaty (2001), Bottero and Ferretti (2010a), Molinos-Senante et al. (2015), Chen et al. (2019a) and Mu and Stern (2018) among others.

After more than 20 years since ANP's appearance in the literature, it has received wide attention (Chen et al., 2019a). Nonetheless, some studies have unveiled that some reports of these ANP studies are incomplete or deficient, raising questions on their overall validity (Mu et al., 2020). Hence, an ANP research best practice checklist has been proposed to authors, publishers and the AHP/ANP community in order to facilitate evaluation, validation and replicability of the studies (Mu et al., 2020).

Some of the proposed items, due to their relevance, may be examined in the context of decision-making processes in STUD, since they inform the whole decision process and facilitate understanding how sustainable and participative approaches were handled:

1. Model development: Studies must provide an explanation of how the model came about, as well as some aspects such as who developed the model? How was the model developed? Decisions models can be developed by the authors, experts and participation of stakeholders. Authors should indicate which approach was used, indicating the number of participants and their qualifications to participate as appropriate.
2. Providing, defining, and sourcing the model factors/nodes: Each element (criteria, alternatives, clusters) must be provided, defined and sourced. A detailed list or table may be provided with the description and the sources of the variables (experts opinion, stakeholders, literature. . .).
3. Group decision aggregation method and consistency: It is important to provide clear information about how the different points of view of the participants were obtained, treated and aggregated. In ANP, group participants' opinions may be aggregated using the geometric mean of the individual pairwise comparison (PWC) judgments or of the individual final priorities. When the aggregation takes place at the PWC level, inconsistencies may appear among the different participants. Hence, it is important to mention how inconsistency was addressed and if a consistency threshold was explicitly stated.
4. Sensitivity Analysis: Once the results are obtained a sensitivity analysis can be performed. It may be addressed at different levels (cluster, alternative or criteria), indicating which sensitivity analysis was chosen and why is also important.

After having discussed the theoretical underpinnings of ANP and STUD for the present study, a systematic literature review was conducted to identify the studies to be included to address the intended research objectives:

1. Explore the nature of ANP use in sustainable development (SD) studies.
2. Examine in depth ANP use for sustainable development territorial/urban (STUD) applications.
3. Determine the extent of proper use of ANP in STUD applications in terms of stakeholder engagement.
4. Determine the extent of proper use of best research practices in ANP STUD applications.
5. Provide recommendations to optimize ANP studies in sustainable development.

3 Research Design

The study was defined in three main phases (Fig. 3). The first one is a survey of ANP and its applications in SD using a systematic literature review following the guidelines proposed by Denyer and Tranfield (2009), Dixon-Woods et al. (2006) and Xiao

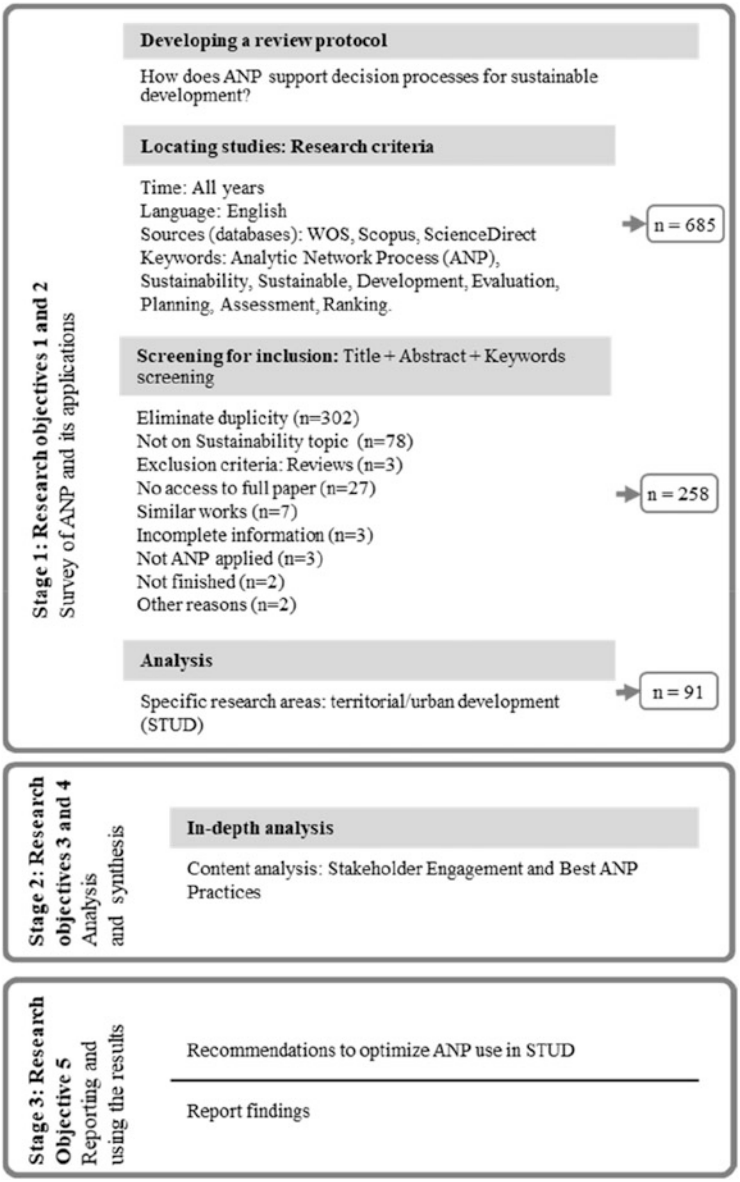

Fig. 3 Process of the systematic literature review

and Watson (2019). This literature review process was informed by previous reviews (Dos Santos et al., 2019; Mu et al., 2020; Lubberink et al., 2017).

The systematic literature review was conducted on all ANP studies published until 2019 in the area of SD. The question formulation was "How does ANP support decision processes for sustainable development?". Search keywords such as "Analytic Network Process (ANP), sustainability, sustainable, development, evaluation and planning were used. This review was a 10-month process consisting of a five-stage process in which 258 papers were identified in the field of SD and were next classified into specific research areas such as territorial/urban development (STUD) where 91 studies were identified and were subsequently used in the next phase (Appendix 1).

In the second phase, the 91 manuscripts were analyzed in-depth according to content analysis (Gläser & Laudel, 2013) based on a list of variables (Table 1). The content analysis was carried out with the assistance of a computer-assisted qualitative data analysis software (nVIVO© software) and Excel. The goal in this phase was to determine the specific STUD applications of ANP which will allow the in-depth analysis of (1) the extent to which stakeholder engagement was addressed and (2) best research practices followed (research objectives 3 and 4).

Finally, in the third phase recommendations to optimize ANP use in STUD were proposed based on the findings.

4 Analysis and Results

The papers were evaluated to check for the presence of the variables identified in Table 1. Whenever, the answer to any of the questions in the table was affirmative for a given paper, a 1 was coded for that variable in the selected paper. The purpose of this analysis was to establish the % of papers that met each of the criteria questions from Table 1. A previous pilot was run by the authors to ensure the questions were actionable and there was a common understanding of how to use them in the evaluation. For the final evaluation, the papers were equally and randomly distributed among the authors for their analysis. The results are reported next. Objectives 1 and 2 of the analysis were addressed during phase 1 of the research, while objectives 3 and 4 were approached during phase 2 of the research. The final objective 5 was addressed during the third and final phase of the research.

Table 1 Variables analyzed in-depth in the content analysis

Part	Variable	Description
Stakeholder engagement	Stakeholder Identification (S-Id)	Have the stakeholders been identified? 1a Who. The study lists who the stakeholders for the decision are. 1b Why. The study describes why each stakeholder is such.
	Stakeholder Prioritization (S-Pr)	Has the relative importance of the stakeholders been established? 2a One. Has at least the most important stakeholder been identified as such? 2b All. Has the relative importance of most or all the stakeholders been established?
	Stakeholder Perspectives (S-Ps)	Have the different stakeholder perspectives been considered in the decision? 3a Some. Were some perspectives taken into account and how? 3b All. Were all/most perspectives taken into account and how?
	Stakeholder Participation (S-Pa)	To what extent were stakeholders involved in the decision-making process? 4a Cons. Were stakeholders consulted, at least at some point, in the decision-making process? 4b Sist. Were stakeholders systematically part of the decision-making process?
Best ANP practices	Model development Explanation (MODEL)	6a. Who developed the model? 6b. How was the model developed? 6c. Have authors indicated the number of participants and their qualifications to participate?
	Clusters/nodes explained (FACTOR)	7a. Are clusters and nodes clearly identified/labelled? 7b. Are they clearly defined, indicating how they will be measured and used? 7c. Are the sources for the cluster/node cited?
	Group decision aggregation (G-CONSIST)	If group decision-making: 8a. How were the opinion of the participants collected and aggregated?
	Consistency (G-AGGREG)	9a. How was group consistency addressed? 9b. How were inconsistency situations addressed? Is a consistency threshold explicitly stated?
	Sensitivity analysis (SENSITIVITY)	10a. Was sensitivity analysis developed? 10b. Which sensitivity analysis was chosen and why?

4.1 Objective 1: Results for ANP and Its Applications in Sustainable Development

Regarding the application of the ANP, the manuscripts were analyzed using two different classifications concerning their application area (primary classification) and particular area (secondary classification) (Dos Santos et al., 2019).

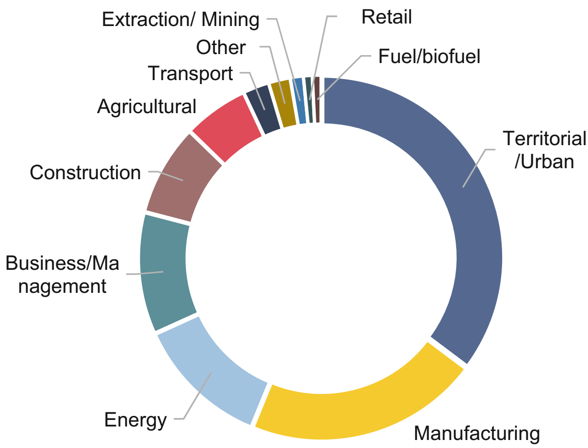

Fig. 4 Number of manuscripts per Application area

The primary classification means knowledge fields in which ANP was used to support decision-making (Dos Santos et al., 2019). 11 different application areas were found: Territorial and urban studies have the largest numbers of manuscripts (Habib & Sarkar, 2017), followed by Manufacturing (Denyer & Tranfield, 2009), Energy (Bourne & Weaver, 2010), Business and Management (Sharpe et al., 2021), and Construction (Kates et al., 2005); meanwhile, Agricultural (Goodland, 1995), Transport (Boyko et al., 2006), Extraction/Mining (Saaty, 1996), Fuel/biofuel (Sipahi & Timor, 2010) and Retail (Sipahi & Timor, 2010) areas gathering a small fraction. Five contributions on specific application areas have been located in the 'Other' group (Fig. 4).

Within each previous area, four different particular areas were defined. This secondary classification details the section or specifies the target in the area in which ANP is applied:

– Decision-making on **Product development**: decisions related to the implementation of concepts, processes or strategies that seek sustainability in the conception of products, e.g. Analyzing alternatives in reverse logistics for end-of-life, product design, etc.
– Decision-making on **Planning of sustainable issues**: managing or planning aspects to be sustainable or implementing sustainable concepts at a micro level in organizations, institutions or small units, e.g. Drivers and Barriers to sustainable implementations, sustainable strategies, Supply chain management, corporate social responsibility, etc.
– Decision-making on **Assessment of sustainable aspects**: evaluation of sustainable characteristics or features, e.g. Suppliers' evaluation, Corporate sustainable practices, environment livability, etc.
– Decision-making on **Sustainable Development**: planning processes based on strategies and actions to bring the human-environmental, social and economic systems closer to sustainability. This group includes works that seek

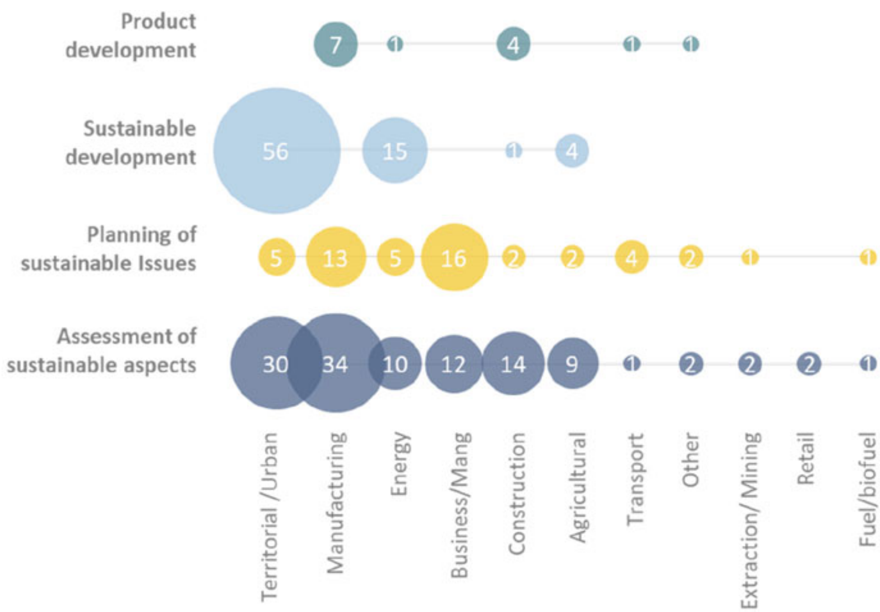

Fig. 5 Number of manuscripts by Particular vs. Application areas

sustainability at a broader level as well as enhancement and maintenance of human well-being in the long-term.

Applications regarding assessment of sustainable aspects are the most common (45%), while the Product development area has the smallest portion of manuscripts (5%). Particular vs. application areas analysis (Fig. 5) indicated that the largest group of documents is concentrated in the particular area of Decision-making on SD for Territorial applications (Xiao & Watson, 2019). Another significant number of manuscripts belonging to the Assessment area are applied in Manufacturing (Prell et al., 2009) and Territorial (Bourne, 2020) groups. Planning of sustainable issues involves mainly Business/Management (Mensah, 2019) and Manufacturing (Wentworth, 2012) applications. And a few applications in Product development are on manufacturing (Bottero & Mondini, 2008).

4.2 *Objective 2: Results for ANP Extent and Nature of Use in STUD Applications*

The *Sustainable Development Territorial and Urban (STUD)* area is the most important application area of ANP supporting decision-making for SD. Models built in this area are mainly aimed at sustainability through:

- Land and coastal planning: criteria selection for land use (Pourebrahim et al., 2010), evaluation of projects for protected areas (Wang et al., 2014a), infrastructures planning (Grimaldi et al., 2017; Tadic et al., 2019; Pourebrahim et al., 2011), or analysis of land suitability (Ferretti & Pomarico, 2013);
- improving of urban areas to improve: growth (Bottero & Ferretti, 2010a; Daneshvar et al., 2017; Khoshnava et al., 2019a), redevelopment (Palmisano et al., 2016), regeneration (Huang & Wey, 2019; Della, 2019; Manupati et al., 2018; Wang et al., 2013a), mobility (Wey et al., 2016; Sayyadi & Awasthi, 2018) or policies (Persada et al., 2018);
- generating indicators and evaluating: land quality (Peng, 2019; Chen & Tsai, 2017), cities' performance (Baldemir et al., 2013; Tao, 2019), risk (Ferretti et al., 2014; De Brito et al., 2018), existing infrastructure (Chen et al., 2018; Isaacs et al., 2008) or living conditions (Dezhi et al., 2016; Zou et al., 2018; Ferwati et al., 2019);
- planning to develop tourism sector (Gonzalez-Urango & García-Melón, 2018; Zarei et al., 2016; Chen & Tzeng, 2010); and
- location of new infrastructures: (Li et al., 2016; Wu et al., 2016; Habib & Sarkar, 2017); and
- resources management: water (Agarwal et al., 2013) or forest (Grošelj et al., 2016); among many others.

The concept of SD used in these studies is basically based on the Brundtland definition. Models are focused on environmental sustainability and social dimension. The sustainable approach is applied to maintain and manage natural resources and waste management while social sustainability tries to respond to the needs of the population.

The 54 manuscripts in the area of *Manufacturing* are concentrated on evaluating and selecting suppliers based on green principles for different types of industries (Kuo et al., 2010; Chung et al., 2016a; Phochanikorn & Tan, 2019); developing green or sustainable supply chains (Al-Mutairi et al., 2019; Hidayati & Hasibuan, 2019); design of products (Soota, 2017; Jayakrishna et al., 2015; Wang et al., 2014b) and designing and evaluating strategies for more sustainable operations and practices (Souza Farias et al., 2019; Ocampo & Ocampo, 2015; Tseng et al., 2009; Aminuddin et al., 2014).

The SD approach is developed to tackle the unsustainable pattern of consumption and production. Manuscripts try to propose sustainable management models, which are environmentally effective and economically affordable, but also socially acceptable (Tseng et al., 2009). Translated into production practices, resource consumptions, raw materials, economic performance and with social benefits to workers, and community. Models are based on the streams of green supply chain management (GSCM), environmental sustainability, ecological performance or Life Cycle Assessment (LCA). Some of the models consider stakeholders' interests (Ocampo & Promentilla, 2016). One particular work incorporates knowledge management and SD with extensive consideration of the economic, environmental, societal, relational, resilience, long-term and operations aspects (Wu et al., 2019).

Energy area is one of the most mixed areas. We found works to guide decision-making in, among others, planning and evaluation of energy sources at different levels (Buyukozkan & Guleryuz, 2016; Koene & Bueke, 2007; Calabrese, 2013); and strategies, practices and drivers for the energy industry (Zhao & Li, 2015; Chen et al., 2015), for countries (Ren et al., 2015; Koene et al., 2015; Ervural et al., 2018) or for some specific sectors such as tourism (Hu et al., 2013). The SD approach is focused on the environmental dimension in order to achieve the efficient use of energy and the use of renewable energy sources.

Manuscripts in *Business or Management* mainly cover model planning and evaluation of corporate practices (Tseng et al., 2011; Chung et al., 2016b; Horng et al., 2018), supply chain (De Felice et al., 2013; Hussain et al., 2016; Malviya et al., 2018) and strategies (Dong et al., 2019; Hsu et al., 2011). Some other studies consider sustainable operations (Duman et al., 2018), risk assessment (Yilmaz, 2008) and investment decisions (Tsai et al., 2009). The SD is translated into the environmental dimension and social impact. Models are associated with management systems such as ISO 9001, ISO 14001, SA 8000 and OHSAS 18001. The stakeholder dimension is also considered.

In the *Construction* area, the development of models is aimed at evaluating existing infrastructures (Hu & Zhang, 2013; Wang et al., 2018; El Chanati et al., 2016); and planning of efficient use of resources (Liu et al., 2018a; He et al., 2017), materials (Khoshnava et al., 2018; Mahmoudkelaye et al., 2018), or technologies (He et al., 2017); as well as generating fewer emissions (Wang et al., 2016). In these models, the environmental dimension is the most common, related to energy use, emissions and materials.

The *Agricultural* area embraces sustainable frameworks to improve land and coastal conditions (Mohammadi et al., 2015; Sajedi-Hosseini et al., 2018; Parra-Lopez et al., 2008) or to develop operations through some practices, (Yang & Liu, 2012) improving the supply chain (Chauhan et al., 2019) or using new technology (Reig et al., 2010). The environmental dimension is the most used to tackle the SD.

Another group of contributions in the *Transport* area implement models to develop alternatively fueled vehicles (Chang et al., 2015), improve the logistics industry (Lam & Dai, 2015; Lam & Lai, 2015) or other transport industries (Dimic et al., 2016; Chen & Ren, 2018). Ecological criteria are the most used to evaluate the use of fuels and emissions.

The *Extraction/mining* sector is aimed at selecting a best timber extraction method (Jaafari et al., 2015) and to assess green supply chain practices (Kusi-Sarpong et al., 2016; Raut et al., 2018). For the Retail and Fuel sectors, we found more supplier selection cases (Wu et al., 2013; Zhou & Xu, 2018; Buyukozkan & Berkol, 2011); and the development of a sustainability index for a biofuel industry (Ngan et al., 2018).

Finally, in the group 'Others' there is a guide for green software developers (Koçak et al., 2014), a list of criteria to evaluate global sustainability of hospitals (Bottero et al., 2015) and in the healthcare sector (Leksono et al., 2019), a learning technology intervention (Raji & Zualkernan, 2016) and a model to improve collaborative innovation networks (Fang et al., 2018).

4.3 Objective 3: Extent of Stakeholder Engagement in Planning of Sustainable Territorial and Urban Development STUD

Due to the openness of the concept to tackle different types of problems, stakeholders were integrated into decision processes as 'interested parties', 'participants' or even 'experts'. In Table 2 shows the general results of the analysis of the stakeholder engagement.

Stakeholder Identification (S-Id)
A detailed and transparent identification process should be the first step in order to ensure a better engagement of stakeholders. The study must provide a list of the interested actors concerning the problem.

Two aspects were analyzed. If stakeholders are at least mentioned (S-Id Who) and an explanation as to why they are considered as stakeholders (S-Id Why) for the decision process is given. In the first case (S-Id Who), 34.8% of the cases mentioned at least some of them. In this case, some studies involved some of them as experts for the design and development of the model, for instance, (Peng, 2019) involved nine experts that represent or know what the stakeholders need. They belong to certain groups such as community development and governmental sector. A few studies also develop an exhaustive list or include a detailed explanation about the techniques used for their identification. For instance, Najafinasab et al. (2015) used a named HYDRA technique, similar to a snowball, for selecting one groups for each pillar of sustainability.

A deeper analysis revealed that only 14.6% of the cases report the reasons why (S-Id Why) each stakeholder group actually constitutes a valid stakeholder (Molinos-Senante et al., 2015; Falcone, 2019; Peris et al., 2013).

Stakeholder Prioritization (S-Pr)
When a list of stakeholders is identified, some techniques may be used in order to establish their relative importance. Only 19.1% of the cases has identified at least the most important one (S-Pr One), and just three studies (3.4%) establish and report the relative importance of all stakeholders (S-Pr All).

In the first group, the most common practice is to identify and include only those stakeholders who, in the authors' opinion, are the most important and include them among the group of experts. For instance, (Ha et al., 2011) selected 57 people from civic groups for a decision on transit-oriented development (TOD) and (Falcone,

Table 2 Stakeholder engagement in sustainable territorial and urban development STUD

	Stakeholder identification S-Id		Stakeholder prioritization S-Pr		Stakeholder perspectives S-Ps		Stakeholder participation S-Pa	
	Who	Why	One	All	Some	All	Cons	Sist
Present	34.8%	14.6%	19.1%	3.4%	40.4%	13.5%	36.0%	11.2%
Absent	65.2%	85.4%	80.9%	96.6%	59.6%	86.5%	64.0%	88.8%

2019) determined the importance among the stakeholders identified according to their time in the sector.

While Grošelj and Stirn (2015), Palmisano et al. (2016) and Gonzalez-Urango and García-Melón (2018) provide a quantitative approach for prioritizing stakeholders, the first one, defined four stakeholder sectors and weighted them by pairwise comparison to establish which sectors were more important for decision-making regarding the development of a region; the second one included a cluster called stakeholders in the ANP model; and the last one, proposed an influence analysis based on Social Network Analysis SNA to study their relationships and define the most influential ones.

Stakeholder Perspectives (S-Ps)

Including different stakeholder perspectives is the most common way of engagement (S-Ps Some). Still, only 40.4% of the cases acknowledge inclusion of the different points of view of the stakeholders. The most common strategy is to include some of them as subject matter experts. However, some authors decide to previously consult with stakeholders in order to aggregate their interests or perceptions in a certain stage of the model. In this case, it is possible to use some techniques such as a surveys (Persada et al., 2018), interviews (Zhang & Wang, 2015), or consider the requirements of the American Customer Satisfaction Index (ACSI) (Chen et al., 2018).

In contrast, only 13.5% of the cases make a clear effort bearing in mind the perspectives of all/most stakeholders (S-Ps All); that is, involving broader groups of stakeholders. For instance, including clear criteria that reflect different stakeholders' interests (Sarvari et al., 2019), or developing different rounds or focus groups during all the stages to confirm the results (García-Melón et al., 2012).

Stakeholder Participation (S-Pa)

Finally, the most common way of involving stakeholders is to consult them at least at some point in the decision-making process (S-Pa Cons), as was done in 36.0% of the models. Using some of the techniques mentioned in the previous section, the stakeholders are mainly involved in verifying the relevance of the criteria (Zhang, 2016), to test the availability of the information (Giordano et al., 2010), or by including stakeholders as experts in the comparison stage (Della, 2019).

Meanwhile, the effective and systematic inclusion of stakeholders (S-Pa Sist) in decision-making in STUD is reported by just 11.2% of the manuscripts. Three examples of good reporting are De Brito et al. (2018), Grošelj and Stirn (2015) and Peris et al. (2013). All of them are particularly interesting since stakeholders were greatly involved in the overall decision rather than making a one-off contribution. Moreover, they include some feedback stage to confirm the results or the proposed methodology, e.g., informing stakeholders about the global and the individual rankings, or collecting their opinions through a questionnaire or a web platform.

4.4 Objective 4: Use of ANP Best Research Practices

In Table 3 shows the general results of the analysis of ANP best practices. The analyzed variables in the selected manuscripts reflect the main stages of a decision-making process. The decision model is fundamental not only for ANP but also for any MCDM analysis. Therefore, who built it and the process followed for this is important to give validity to the study as we previously mentioned in Sect. 2.2.

Model Development (MODEL)
We explored whether authors provide the approach used to develop the models, indicating the number of participants and their qualifications to participate as appropriate. From the papers selected, 76.9% made this explicit.

The number of experts varied greatly according to the type of problem, and the way the model was approached. Cases that only developed the evaluation at the criteria level were likely to include more participants. In general, we looked at models from one to 91 participants. The most common range was approximately from 2 to 20 participants. However, there were some exceptions: between 28 and 75 participants (Molinos-Senante et al., 2015; Pourebrahim et al., 2010, 2011; Palmisano et al., 2016; Dezhi et al., 2016; Chen & Tzeng, 2010; Ha et al., 2011; Chuang et al., 2018).

It was also common to involve a larger group in the early stages and a smaller one later. Chen et al. (2018) included 91 expert opinions regarding the construction of rural infrastructures; however, the evaluation was different. Each one ordered the criteria according to their importance and then the authors calculated a score value according to the ratio of accumulated weighting previously received. Lee and Chi (2010) first, defined a list of 100 experts and sent questionnaires to assess criteria in the early stage, 56 questionnaires were returned. The completed pairwise comparisons were sent to those 56, and 36 questionnaires were returned.

As in AHP, in ANP the quality of the experts is more important than the quantity (Saaty, 1999) and explicitly, ANP does not need a big sample size (Ferwati et al., 2019). Nevertheless, models should report the profile or expertise of the participants. The common profiles were academics, members of governments and public agencies, and specialists in the subject to be discussed, for instance, engineers, environmentalists, GIS specialists, transport planners, tourism or sustainability planners. Urban planners or developers are a little less common, and the least common are social actors like civil or resident groups, private entities, or NGOs.

Usually experts were selected because they belonged to a certain group or institution (Molinos-Senante et al., 2015; Huang & Wey, 2019; Zou et al., 2018; Alizadeh et al., 2018), on the basis of their specific competences in certain fields

Table 3 ANP best practices in sustainable territorial and urban development STUD

	Model	Factor	G-CONSIST	G-AGGREG	Sensitivity
Present	76.9%	63.7%	42.9%	30.2%	18.9%
Absent	23.1%	36.3%	57.1%	69.8%	81.1%

(Grošelj et al., 2016; Giordano et al., 2010), due to their years of experience (Xia & Cheng, 2019), or for their interest in the problem (Grošelj & Stirn, 2015). Only a few of the manuscripts detailed the selection processes. De Brito et al. and Gonzalez-Urango and García-Melón (De Brito et al., 2018; Gonzalez-Urango & García-Melón, 2018) proposed an influence analysis based on Social Network Analysis SNA to select a list of experts. Other experts were invited based on purposive sampling methods such as Ferwati et al. (2019), or using a named HYDRA technique, similar to a snowball, for selecting one group for each pillar of sustainability (Najafinasab et al., 2015).

Two manuscripts calculated sampling sizes before consulting experts. Sarvari et al. (2019) used the Cochran formula according to the unknown population, where 65 people were selected as the sample size. Respondents were carefully selected, based on their degree, level of experience, and their profession. In an early stage 48 completed questionnaires were collected. Then, six experts were selected to answer an ANP questionnaire based on their level of experience, background, and their authorization. Finally, Khoshnava et al. (2019b) considered the random sample method used for an equal geographic spread amongst samples. According to this around 100 questionnaires were distributed to postgraduate students and researchers who were familiar with some terms.

Model Factors (FACTOR): Clusters and Nodes

Three aspects were checked: If clusters and nodes were labelled, clearly defined, and the source specifically cited. 63.7% of the manuscripts meet at least two of these requirements.

In terms of identification of the elements, listing the elements is the most common practice. An analysis of the most common words among clusters and criteria shows that the most common tags are related to the terms: environment or natural, economic and sociocultural/social/socio. All of them are proposed to evaluate or regard appraisal aspects such as uses, quality, density, population, risks, distances, infrastructures or facilities, costs, size, plans, employment, landscape and ecosystems, features, access, intangible values, tendencies, impacts and waste. Few recent works include technological (Ghaemi Rad et al., 2018) and political factors (Baldemir et al., 2013).

Regarding the number of elements in a cluster, it should be no more than seven, although nine may be acceptable (Saaty & Vargas, 2006). There is no consensus or general recommendation as to the number of criteria and alternatives a model should have, although it is recommended that the fewer the better so the number of pairwise comparisons is minimized.

Concerning the criteria, the most common are models with less than 30 criteria. However, Sayyadi and Awasthi (2018) propose a model consisting of three criteria (congestion, fuel consumption, and emission) used to evaluate five transportation policies. Alternatively Baldemir et al. (2013) present a model that consists of 7 main and 59 sub-criteria which were determined and published by the Cittaslow International network to select the most appropriate candidate to be a slow city among 7 options in Turkey. Also noteworthy are the works of Giordano et al. (2010) with

49 environmental indicators for evaluating logistic settlement and Wolfslehner et al. (2005) with 43 indicators for evaluating four sustainable forest management strategies.

Regarding the alternatives, most models have between 3 and 5 alternatives. These are mainly strategies, scenarios, locations, projects, policies, uses, sites, methods, technologies or programs. The lowest number, two alternatives, is found in Dragoi (2018) about joining or not joining non-industrial private forests into a single management unit. The work of Wang et al. (2013b) is interesting since it includes 80 project alternatives to be evaluated. ANP is used to determine the weight of the evaluation criteria, and once defined the evaluation of the alternatives is carried out using the absolute measurement method to compute the rating scores for each alternative (project).

The second factor concerning the definition indicating how elements will be measured and used is the least reported.

Informing about the source of the elements is increasing considerably. The most common ways of defining clusters and nodes are through a literature survey and expert consultants. Expert opinion is collected through questionnaires (Aminu et al., 2017), interviews (Huang & Wey, 2019; Wang et al., 2013a; Zou et al., 2018; Ferwati et al., 2019; Zhang, 2016), discussion meetings (Sayyadi & Awasthi, 2018; Wang et al., 2010), or focus groups and workshops (Pourebrahim et al., 2011; Ferretti & Pomarico, 2013; Huang & Wey, 2019; Wey et al., 2016; Wu et al., 2016; Ferretti, 2011; Arsic et al., 2018).

Other sources for element screening are the authors' knowledge (Chen & Khumpaisal, 2009); empirical data availability (Huang & Wey, 2019; Habib & Sarkar, 2017; Choubin et al., 2019); and the use of indicators proposed in current rating systems or guides, such as, the Cittaslow International Network (Baldemir et al., 2013), the Customer Satisfaction Index (ACSI) (Chen et al., 2018), or local plans (Pourebrahim et al., 2010; Najafinasab et al., 2015; Wang et al., 2013b; Ferretti, 2011; Gonzalez-Urango & García-Melón, 2017).

Aggregation of Judgments: Group Perspective Aggregation (G-AGGREG) and Consistency (G-CONSIST)

Once the model is agreed upon, PWC judgments are required. Questionnaires based on pairwise comparisons are the most frequent way to obtain expert opinions. It is less common to request judgment from the panel of experts and stakeholders during workshops or focus groups that allow for open discussion among participants (Pourebrahim et al., 2011; Ferretti & Pomarico, 2013; Ferretti et al., 2014; Peris et al., 2013; Giordano et al., 2010; Wang et al., 2013b). Hence, it is important to know how inconsistency was avoided and individual results were aggregated.

57.1% of the manuscripts do not mention the treatment of the consistency. Moreover, it is odd that some studies with big samples do not have evidence about it. The consistency ratio C.R. ≤ 0.10 is considered acceptable in 41.8% of the cases, which is consistent with common practice (Saaty, 1996, 2001). Just Groselj and Stirn (2015) decided to allow CR ≤ 0.15. This adoption did not change the final results, but it helped participants significantly. This strategy can be acceptable depending on the nature of the problem, the complexity of the model or the expertise of the participants.

Only three particular applications have applied different proposals. Garcia-Melon et al. (2012) using the Delphi methodology through several rounds that allow participants' judgments to be adjusted as they become aware of the group's judgments. Wang et al. (2013b) classified experts in groups. One core team familiar with the ANP approach, determined the comparison on a consensus basis; then, other members were consulted for revision and adjustment of the evaluation scores; and finally, results were also discussed among the other team members for validation of the reasonability. Lastly, Grimaldi et al. (2017) determined groups of DM. Each group was associated with a corresponding cluster and made the comparisons between nodes with respect to their specific cluster.

After questionnaires are returned to the facilitators, results should be combined. A minority of papers (30.2%) were clear about the approach used. Saaty (1996) claims that the geometric mean is the most suitable aggregation technique to obtain the overall results. Indeed, the most common way of integrating experts' opinions is through a geometric mean, aggregating individual priorities (AIP) or aggregating individual judgments (AIJ). Indeed, AIP and AIJ are the common procedures. Still, some authors propose an applied arithmetic mean to aggregate experts' opinions (Ferretti & Pomarico, 2013; Huang & Wey, 2019; Wang et al., 2013a; Chen & Tsai, 2017; Zou et al., 2018). Wey et al. (2016) propose that if each expert represents the viewpoints of a different group the samples are independent of one another, therefore using the arithmetic mean is a suitable calculation approach; if the samples are interrelated, then the geometric mean would apply.

In a few studies Hopwood et al. (2005) the different experts worked together in order to achieve a consensus. Finally, Palmisano et al. (2016) combined both approaches since they determined four categories of stakeholders. The consensus vote on judgements was adopted to obtain the local priority vectors of each group of stakeholders and the geometric mean was applied to aggregate the local priority vectors of each group of stakeholders.

Robustness of the Model: (SENSITIVITY)

Sensitivity analysis is the procedure undertaken to study the robustness of a model. However, it is not as common a practice as it should be. Only one-fifth (18.9%) of the analyzed documents presented any kind of sensitivity analysis. This result is similar to those found by Mu et al. (2020). Hence, we can suggest that avoiding sensitivity analysis is a common bad practice.

Sensitivity analysis should be addressed after final priorities are obtained, but as it is an uncommon practice, some models' developers could consider that it is unnecessary to report it. Other possible explanations for the lack of this analysis could be that it may be difficult to find an established, clear and strong sensitivity approach to follow. Also, there are not enough references about the level and the type of analysis required, examples of questions used to validate the result or descriptions of the impacts of sensitivity analysis.

Still, some authors proposed some interesting procedures:

- Changing the priorities of all criteria (Wang et al., 2013a; Arsic et al., 2018; Arabsheibani et al., 2016).
- Changing criteria with higher scores (Palmisano et al., 2016; Razavi Toosi & Samani, 2014).
- Changing the cluster weights (Grimaldi et al., 2017; Razavi Toosi & Samani, 2016). Ferretti (2011) presented a sensitivity analysis featuring five scenarios of changes in clusters weights.
- Modifying the influences of the element with the highest weight (Molinos-Senante et al., 2015). Bottero and Ferretti (2010b) modified the influences of the alternatives on the criteria and vice versa.
- Eliminating one alternative at a time and checking the resulting ranking (Bottero & Ferretti, 2010b).

Furthermore, to evaluate the robustness of a model Choubin et al. (2019) used the Receiver Operating Characteristic or ROC approach to measure the overall performance of predictive models. Aminu et al. (2017) proposed two statistical analyses (Kolmogorov–Smirnov K-S test and t test) for priority weights validation.

4.5 Objective 5: Recommendations to Optimize ANP Applications in Planning of STUD—Future Applications, Recommendations and Emerging Topics

Based on our systematic review of the literature and the analysis of selected studies in terms of stakeholder engagement and ANP best research practices, the following recommendations are provided:

Regarding the participation of stakeholders in the decision-making process: The treatment of multiple stakeholders is one of the main challenges when making decisions related to STUD problems. ANP is helpful to increase the number of expert participants and to include intangible criteria and subjective judgments in the decision-making process. Expert selection should include representatives and relevant stakeholders as decision-makers in the decision-making process (Šijanec et al., 2014). Different approaches could be explored to respond better to this challenge, for instance, integrating the preferences of other interest groups such as civil organizations and residents (Molinos-Senante et al., 2015; Gonzalez-Urango & García-Melón, 2018).

The challenge is therefore to increase the number of participants in prioritization tasks, using participative approaches to solve discrepancies among participants but also improving the engagement and the quality of the deliberation itself and fostering a common language and understanding of stakeholders (Peris et al., 2013; Wolfslehner & Vacik, 2008). The treatment of multiple participants is an interesting line. Methods that involve different opinions should consider methodological complements (Sierra et al., 2018). We identified the following strategies for involving stakeholders, according to the interest of the decision maker or the available resources. It would be possible to implement one or more of these: focus groups or workshops (Giordano et al., 2010); organized actions groups (Arsic et al., 2018); promoting discussion at all stages to build consensus (García-Melón et al., 2010); enabling their inclusion at particular stages (Grošelj et al., 2016; Grošelj & Stirn, 2015); including a cluster called stakeholders in the model (Palmisano et al., 2016); giving a leading role to a certain group e.g. users (Chen et al., 2018); or studying their relationships and selecting just the most influential ones (De Brito et al., 2018; Gonzalez-Urango & García-Melón, 2018).

In this line, issues of aggregation and consensus appear. How to aggregate individual judgments and how these influence the final ranking (Razavi Toosi & Samani, 2014) is still one of the problems in group decision-making. Some of the proposals are: assigning weights to participants' evaluations; assigning cluster evaluation to a certain group of stakeholders; aggregating preferences by groups to discover underlying conflicts and then tackling them openly; discarding the results of less influential or incoherent stakeholders before aggregating individual results; arranging meetings or evaluation rounds to obtain a greater convergence among the stakeholders' positions; or integrating different perspectives in the assessment and then comparing results from each group.

Regarding best practices when applying ANP:
A great deal of attention should be devoted to the design and reporting of the studies. Both the way the model is built and the results must be carefully reported. The design phase of the models must be explained in detail, describing who participates, their suitability to participate, as well as the sources of information consulted and the techniques used for the design of the models. Involving some additional methods which may extract information from a broader set of elements may be included. The application of Delphi, interviews or surveys has been used in the definition of some models (Šijanec et al., 2014).

In the design of the model, small and balanced clusters have to be considered, clusters that are easily manageable by the decision-makers (Ferretti, 2011). Models should also include influence criteria and decision variables that can easily be interpreted, calculated and compared (Zhang, 2016; Wang et al., 2013b).

Attention should be paid to the elaboration and reporting of questionnaires. It is possible to simplify the questionnaire design and the comparison process must be helped by a facilitator (Bottero & Ferretti, 2010a; Li et al., 2016; Wolfslehner et al., 2005). An extra recommendation is the development of user-friendly, intelligent or dynamic linguistic software approaches and graphic interfaces to further promote and support better applications in order to provide better and appropriate means of communication (Wolfslehner et al., 2005; Wang & Zeng, 2010). Online collaborative tools can help to fill the gap between civil society and experts (Ferretti, 2011), to achieve a better understanding of participants positions (De Brito et al., 2018), as well as to involve multidisciplinary knowledge.

Regarding the evaluation of the robustness of models, some authors decline to compare and combine MCDM methods, others consider that they might be usefully applied, complement and compare results with different approaches or standardization procedures in order to test the robustness of the obtained results (Wolfslehner et al., 2005; Ferretti, 2011) e.g. The financial viability of the projects may be appraised separately by using financial analysis techniques such as the net present value (NPV) and rate of return (Wang et al., 2013b); or testing the proposed model with real data and comparing the results with other comparable studies in the literature (Sayyadi & Awasthi, 2018). Other authors propose statistical analysis for priority weights validation, validation of models and checking the subjective nature of expert opinion (Grošelj & Stirn, 2015; Aminu et al., 2017).

The management of consistency has generated some interest for some authors as well (Dragoi, 2018; Ergu et al., 2014).

Finally, it would be very interesting to introduce and integrate different perspectives of sensitivity analysis at the moment of the evaluation and compare results obtained to learn more about the features and behavior of ANP models (Molinos-Senante et al., 2015; Wolfslehner et al., 2005).

5 Conclusions

This chapter has presented a comprehensive review of all published literature on the application of ANP to STUD issues. The study has been approached from three perspectives. The first and most generic, a systematic literature review has been carried out with a well contrasted review protocol and with the ultimate aim of answering the question How does ANP support decision processes for sustainable development?

Following the application of this systematic review process, a total amount of 685 papers meeting the initial search requirements were selected, from which 91suitable papers for this study (e.g. STUD) were chosen to move on to the next phase of in-depth study. In this second phase, a content analysis was carried out from two different perspectives (1) to analyze the approach and/or use that the different published studies make of stakeholders and their level of involvement and (2) to analyze the procedure of application of ANP as a multi-criteria decision method in order to discover a list of good practices for its future use.

All in all, this article has managed to call the attention on the need of conducting rigorous studies in terms of stakeholder engagement and ANP research best practices. Furthermore, this study draws up recommendations so that the ANP can be applied to ANP studies in STUD.

We can finally conclude that ANP, when properly used, is a suitable tool for STUD assessment and opens a very promising research line not only in STUD research but in the field of Sustainable Development in general.

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Appendix 1: Papers Classified as Territorial/Urban Development (STUD)

Paper_1	Wolfslehner et al. (2005)
Paper_2	Bottero and Mondini (2008)
Paper_3	Isaacs et al. (2008)
Paper_4	Wolfslehner and Vacik (2008)
Paper_5	Chen and Khumpaisal (2009)
Paper_6	Bottero and Ferretti (2010b)
Paper_7	Bottero and Ferretti (2010a)
Paper_8	Chen and Tzeng (2010)
Paper_9	García-Melón et al. (2010)
Paper_10	Giordano et al. (2010)
Paper_11	Lee and Chi (2010)
Paper_12	Pourebrahim et al. (2010)
Paper_13	Wang and Zeng (2010)
Paper_14	Wang et al. (2010)
Paper_15	Cui et al. (2011)
Paper_16	Ferretti (2011)
Paper_17	Ha et al. (2011)
Paper_18	Pourebrahim et al. (2011)
Paper_19	Wolfslehner and Vacik (2011)
Paper_20	Wu (2011)
Paper_21	Xu (2011)
Paper_22	García-Melón et al. (2012)
Paper_23	Ghajar and Najafi (2012)
Paper_24	Agarwal et al. (2013)
Paper_25	Baldemir et al. (2013)
Paper_26	Ferretti and Pomarico (2013)
Paper_27	Peris et al. (2013)
Paper_28	Wang et al. (2013a)
Paper_29	Wang et al. (2013b)
Paper_30	Ferretti et al. (2014)
Paper_31	Razavi Toosi and Samani (2014)
Paper_32	Šijanec et al. (2014)
Paper_33	Grošelj and Stirn (2015)
Paper_34	Molinos-Senante et al. (2015)
Paper_35	Najafinasab et al. (2015)
Paper_36	Shehada et al. (2015)
Paper_37	Zhang and Wang (2015)
Paper_38	Arabsheibani et al. (2016)
Paper_39	Dezhi et al. (2016)
Paper_40	Grošelj et al. (2016)
Paper_41	Li et al. (2016)

(continued)

Paper_42	Palmisano et al. (2016)
Paper_43	Razavi Toosi and Samani (2016)
Paper_44	Wey et al. (2016)
Paper_45	Wu et al. (2016)
Paper_46	Zarei et al. (2016)
Paper_47	Zhang (2016)
Paper_48	Aminu et al. (2017)
Paper_49	Chen and Tsai (2017)
Paper_50	Daneshvar et al. (2017)
Paper_51	Gonzalez-Urango and García-Melón (2017)
Paper_52	Grimaldi et al. (2017)
Paper_53	Habib and Sarkar (2017)
Paper_54	Kao et al. (2017)
Paper_55	Pourebrahim and Amoushahi (2017)
Paper_56	Alizadeh et al. (2018)
Paper_57	Arsic et al. (2018)
Paper_58	Chen et al. (2018)
Paper_59	Chuang et al. (2018)
Paper_60	De Brito et al. (2018)
Paper_61	Dragoi (2018)
Paper_62	Ghaemi Rad et al. (2018)
Paper_63	Gonzalez-Urango and García-Melón (2018)
Paper_64	Jesiya and Gopinath (2018)
Paper_65	Liu et al. (2018b)
Paper_66	Liu et al. (2018c)
Paper_67	Manupati et al. (2018)
Paper_68	Nouri et al. (2018)
Paper_69	Persada et al. (2018)
Paper_70	Sayyadi and Awasthi (2018)
Paper_71	Xu et al. (2018)
Paper_72	Zou et al. (2018)
Paper_73	Cerreta et al. (2019)
Paper_74	Chen et al. (2019b)
Paper_75	Choubin et al. (2019)
Paper_76	Della (2019)
Paper_77	Falcone (2019)
Paper_78	Ferwati et al. (2019)
Paper_79	Feyzi et al. (2019)
Paper_80	Huang and Wey (2019)
Paper_81	Kamangar et al. (2019)
Paper_82	Khoshnava et al. (2019a)
Paper_83	Khoshnava et al. (2019b)
Paper_84	Peng (2019)
Paper_85	Putra et al. (2019)

(continued)

Paper_86	Sarvari et al. (2019)
Paper_87	Shafaghat et al. (2019)
Paper_88	Tadic et al. (2019)
Paper_89	Tao (2019)
Paper_90	Thilini and Wickramaarachchi (2019)
Paper_91	Xia and Cheng (2019)

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Environmental Monitoring of the Socio-economic Components of the Impact of a Mega Project

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Abstract Mapping the socio-economic and socio-communicative implications of a mega project in Europe becomes the occasion to fill a gap in the Italian national regulations on the accountability and reporting of socio-economic impacts. A monitoring project is translated into a methodological and experimental proposal to send to the Italian Ministry of the Environment.

A multidisciplinary group has adopted an intervention research approach to design and test a new model that can easily be replicated for other mega projects. The multicriteria modelling and decision aiding way of thinking have been used to propose a critical reading of the model and a methodological approach to data acquisition and multicriteria aid in the monitoring process.

The paper describes the experimental protocol and some methodological analyses and improvement proposals gained from the multicriteria modelling experience.

Keywords Social responsibility of mega projects · Accountability of socio–economic impacts · Multicriteria models · Multicriteria decision aiding

1 Introduction

A multidisciplinary research group is currently involved in one of the most contested megaprojects in Europe, the construction of the high-capacity, high-speed rail line between Turin and Lyon, which includes a more than 50 km long tunnel through the Alps between Italy and France. The European Union and the Italian and French national governments have officially approved the project as part of the

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Mediterranean corridor of the Trans-European Transport Network. However, this happened in direct contrast with some of the local administrators and citizens of the Susa valley, in Italy, who created the No TAV ("Treno ad Alta Velocità"—High Speed Railway) movement. The by now 30 years of the No TAV opposition is somewhat less violent and intense than it was 10 years ago, but it is still witnessed, above all in relation to the setting-up of new construction sites (see Corazza et al., 2021, for the history of this megaproject and the No TAV movement).

The company in charge of the project contacted the research group to map the potential social and economic impacts of the transnational railway project on the territories of reference and to develop and test a monitoring framework of the social and economic impacts generated by the construction sites for the entire duration of the project. This framework, created and tested on this occasion, should fill a gap in the Italian national regulations pertaining to the accountability and the reporting of place-based social and economic impacts generated by construction sites.

A project on the monitoring of these impacts, in the short, medium and long terms (with a time span of more than 20 years), at the construction site scale, and at the municipal, valley and regional levels, was therefore translated into a methodological and experimental proposal to send to the Italian Ministry of the Environment, in compliance with the environmental impact assessment logic.

Contact with the stakeholders became difficult in 2020, as a result of the COVID-19 emergency. Therefore, the multidisciplinary research group focused on the analysis framework, an experimental data acquisition and monitoring protocol. At the end of 2020, the first draft of the framework was drawn up and its line of thought and main concepts were presented in a virtual meeting which involved the company, the Piedmont Region and the main official data sources.

The research group includes people with very different backgrounds: from sustainability accounting to those involved in critical management studies, sociologists, economists, physicists, and circular economy specialists. These figures are not consultants for the company, and the aim of their Interventionist Research (Dumay & Baard, 2017; Jönsson, 2010; Lukka & Vinnari, 2017) is to make a contribution that is theoretical and organisational at the same time in order to (at least) provide elements to help solve a problem.

The intervention of the group is basically focussed on the need to provide an assessment of the socio-economic and socio-communicative implications that may arise due to the megaproject, as explained by the need to reinforce the mandatory environmental assessment required by the Italian Ministry of the Environment (together with the Ministry of Infrastructures and Transport that from 2021 composes the Ministry of the Ecological Transition). On the other hand, the problem situation is extremely interesting, because the complete lack of best practices, not in terms of cases, or as common and shared guidelines, leaves vast occasions to design, experiment and test a new model to account for such impacts. The mainstream practice, in the Italian scenario of megaproject development, has traditionally been to produce assessments that are difficult to replicate, or which are not based on evidence that can easily be retrieved or retrieved in a timely manner. These conditions make the validity test of any model particularly difficult or even impossible.

A new figure, with competency in multicriteria modelling, was included in the multidisciplinary group at the end of 2020, to analyse and improve the draft of the framework from a methodological point of view.

The first suggestions were used to improve the document that was sent to the Ministry in March 2021 (Plan of environmental monitoring of the economic and social components. Focus on Ante Operam 2012–2019). Some data were acquired and analysed before March 2021, and a new data acquisition and analysis step was then activated.

The first section of this paper describes the draft of the experimental protocol, a multicriteria critical reading of some components of the draft and the new version of the document sent to the Ministry.

An analysis of the document and of the data acquisition activity is described in the second section, together with a methodological proposal of data analysis and multicriteria aid in the monitoring process. Some considerations on the possible future use of these proposals are synthesised in the conclusions.

2 Environmental Monitoring of the Economic and Social Components

The aims of the multidisciplinary research group include the formulation of a panel of indicators that should be as open as possible and based on evidence, a verifiable and replicable methodology and the release of data in an open way, all of which make the tool dialogic and transparent.

A literature analysis on large or mega construction projects and their social responsibility and impacts, as well as a comprehensive examination of several reports on the Susa valley economy and mountain condition, were used to identify macro-ambits, ambits and indicators. Objectivity, replicability, easy accessibility and consistency with the Ministerial guidelines for the environmental monitoring (Guidelines for the environmental monitoring project of strategic infrastructures and production facilities, 2003) were considered the main principles to orient the definition of the indicators. The presence of public sources of the required data was considered essential to facilitate future analyses and verifications of the reliability of the proposed procedure.

Six macro-ambits were proposed for the Experimental protocol, and the indicators were associated with specific actions, risks or problems, for employees and the population, and they also included context data. The considered macro-ambits are:

1. *Health and safety* of the employees and population, where health is a physical and psychological state (3 ambits and 6 indicators to indicate the actions adopted by the construction company to guarantee health and safety);
2. *Relational capital* established between the company, institutions and people, which includes both any kind of relationship with the territory and actions oriented towards developing the human capital of the valley (6 ambits and

21 indicators concerning both the connection results and the population state, in terms of development and vulnerability);
3. *Sustainability governance*, in terms of integration of the sustainability and governance structure, at the company level (3 ambits and 12 indicators in relation to the sustainable strategies, but also to the implementation of anti-mafia procedures and certifications and communication with the stakeholders);
4. *Economic consequences* on the territory (9 ambits and 28 indicators of the impact on the local economy, but also on the valley demography and the way of life of the people);
5. *Impact on the mobility of the people*, in terms of traffic problems but also improvement in sustainable mobility (3 ambits and 8 indicators);
6. *Promotion of the territory* and preservation of its cultural capital and identity (5 ambits and 10 indicators, which also include the cultural identity of the bi-national company, where different languages and cultures co-exist).

A methodological analysis of the proposed structure and specific indicators was performed to improve the draft.

2.1 Analysis of the Draft

From the multicriteria modelling point of view, the number of macro ambits and ambits (29) seemed too high, but this is a natural consequence of the literature analysis that led to this structure and a long list of indicators being generated. Proposing a panel of indicators as open as possible is one of the aims of the research group, but a revision, oriented towards the different defined or possible uses of these indicators, would improve the structure and facilitate the development of a verifiable and replicable methodology.

Another point is that some aspects appear in more than one macro-ambit: communication with the stakeholders is present in *Sustainability governance,* but it is also an essential element of *Relational capital;* sustainable mobility improvement appears in *Impact on the mobility of the people,* but it should also be considered a positive consequence of the way of life of the people, which appears in *Economic consequences* on the territory.

During the meeting at the end of 2020, the research group, together with the company and the Piedmont Region, underlined that: (a) different activities (surveillance, attention, intervention) are required in the monitoring process and (b) the company has to be facilitated in the choice of actions that have to be avoided, the impacts that have to be minimised, or at least reduced, in the compensation, reactivation or restoration activities, in the proactive actions and in others that generate positive impacts on the territory. Therefore, the panel of indicators should distinguish a set of specific actions or decisions and the indicators should be associated with these situations.

The draft of the framework distinguished three phases of the monitoring process (Ante Operam, before the opening of the construction sites—AO, during the project in relation to the role of the Construction Sites—CS, Post Operam, when the project has been completed, with a time span of more than 20 years—PO) and the indicators were associated with one or more specific phases. The draft also distinguished between quantitative and qualitative indicators, while a new distinction, more oriented towards the aims of the monitoring activities and the actions or decisions that may be needed, seemed useful. Such a distinction should at least be included in the description of each indicator.

The main distinction should be made between context indicators, which are essential to map the territory and document any socio-economic modification, and the others, which are used to identify situations that require specific actions, decisions or revisions of implemented actions. Monitoring the context indicators allows some critical dynamics to be recognised and reported to the decision makers. The ministerial guidelines for the Environmental monitoring project (Guidelines for the environmental monitoring project of strategic infrastructures and production facilities, 2003 and further updates) propose a list of ambits that should be monitored: population, economic activities, labour market, services and infrastructures, socio-cultural aspects and reconstruction of the main events of the historical evolution. Specific trends, taken from the context indicators, should be analysed by means of other indicators, which can be called decisional indicators. They may be distinguished, for instance, into two categories, the first in relation to risks, communication problems or malfunctions that the construction sites can generate, and the second, which analyses the direct or indirect actions that are positive for the people and territory.

The first category of indicators should be monitored to activate management actions of any foreseen or present criticality. The second should be monitored to evaluate the effectiveness of any action, whether completed or under development, in order to modify it, if necessary, to define new actions or to evaluate the impact of an action on PO. The macro-ambits, ambits and indicators of the two categories should be reorganised, and thus four typologies of data could be distinguished from the structure of the data base:

1. Socio-economic data that describe the territorial situation and its dynamics (which are useful to identify circumstances that require a specific intervention)
2. Data on the activities in the construction sites (which are useful to identify circumstances that require a specific intervention)
3. Data on issues and malfunctions that the construction sites can generate on the territory or people (which are monitored for the risk management or control of the consequences)
4. Data on the developments and effects of direct and indirect actions in favour of the territory (which are useful to evaluate the potential or actual impacts of these actions or to define-modify intervention strategies).

Some of these suggestions were used to improve the draft and generate the document that was eventually sent to the Ministry of the Environment in March 2021.

2.2 The Document

Some data were acquired, between December 2020 and March 2021, in relation to the years 2012–2019, which were considered as the period for the analysis before the opening of the construction sites, and the draft was analysed and improved before sending it to the Ministry of the Environment (whose name was changed in February, by the new Government, to Ecological Transition Ministry).

Each indicator was associated with one of four categories (context, sustainability, construction sites and communication) and a distinction was made between the *main* and *secondary* indicators. Thirty-four of the original eighty-four indicators were considered to be of main importance: thirteen indicators in relation to the socio-economic conditions of the thirty-nine municipalities in the Susa valley and the other twenty-one indicators in relation to the possible direct and indirect effects of the construction sites on the local communities.

The document also included a procedure that could be used to interpret the monitoring results as regards the needed actions. A framework was proposed to evaluate the negative impacts, whenever a counterfactual analysis underlined anomalies in the data trends.

Data pertaining to the main indicators of the context and construction sites were acquired, in relation to the 2012–2019 period, at the valley level (and its 39 municipalities) and their analysis was included in the document. However, these are only quantitative data, because it was very difficult to acquire any qualitative indications.

A methodological analysis of the components of the document is proposed in the next section, together with some proposals for future activities.

3 Methodological Analysis

Three elements should be analysed from a methodological point of view. Two are linked to the essence of the reasoning, and the third is more communicative and related to the aim of proposing a dialogic and transparent tool.

The indicators of the communicative aspect and their descriptions are different, and their nature is sometimes clear and transparent, but in other cases the meaning has to be explained more carefully, and paying attention to the structure of the panel could also facilitate the release of data. This aspect is analysed in Sect. 3.1.

The other aspects are partially connected to each other and to the use of the acquired data. An experimental proposal is presented in the document to interpret the monitoring results. The proposal includes two procedural elements and indicates that their integration should facilitate decision and action.

3.1 The Structure of the Indicators in the Panel

A large number of indicators is often considered a sign of quality and reliability, but this is often not true. In this case, since several indicators were identified for the purpose of creating guidelines for future applications, a distinction between the main and secondary indicators may be useful to reduce the number of indicators and to more easily orient them towards specific monitoring process activities.

However, the nature of this distinction is not so clear. The document specifies that the distinction was made together with the company, when it was the owner of the data, and by means of interviews with the sources of the other data, and it also indicates that secondary indicators could be used in the future. However, it is not clear whether the distinction was made in terms of importance or significance.

An example can help to clarify this remark. There are some indicators in the Education macro ambit that were created in relation to the "Human capital creation by mean of investments in the local population" ambit. Some indicators, such as the number of collaborations activated with technical institutes and the number of participations in courses held by the technical institutes, were considered as secondary indicators. Two different interpretations are thus possible: technical institutes that are consistent with the topics of the mega project are not present in the Susa valley and therefore their involvement is impossible (the indicators are not significant in this specific case), or the data source considered these activities as not being so useful, and such indicators are therefore of a secondary nature, i.e. they are not essential or are unimportant.

In both cases, the secondary indicators can be included in the panel, but the ambiguity that is associated with the nature of the distinction may have influenced the distinction and acquisition processes and can now influence the use of the acquired data.

Four categories are associated with the indicators. Context indicators are useful, above all because these data allow an analysis to be made of the territory and its socio-economic aspects before the construction sites are opened, in a period characterised by an economic crisis in Italy and, above all, before the COVID-19 emergency that has blocked tourism and several activities since March 2020. The document explains that some context indicators are not clearly associated with the existence of the construction sites, but they should be monitored because they facilitate an analysis of the processes that could have generated some changes on the territory.

The principle is clear and the indicators are annotated in detail in the document. However, some indicators are not so clear. Another example is also associated with the mega Education ambit and the "Human capital creation by mean of investments in the local population" ambit. There are some main indicators in this ambit, and two are context indicators: the number of students in the technical institutes and the number of courses held for professional qualification and/or re-qualification that the Region activates throughout the territory involved in the mega project.

The first indicator can be used to identify the used interpretation of the "secondary indicator" concept in this ambit. At the same time, the indicator description underlines that the context indicator is not a sign of a possible and direct impact of the construction site, and is instead an element of the education dynamics, because there is evidence in the literature that the territory is interested in being involved in the progress that the project will induce. However, the nature of the induced progress is not so clear in this case and should be explained more clearly.

The second indicator presents another ambiguity: are the courses a consequence of the mega project (i.e. an element of the required compensation) or a sign of the phenomenon described in the literature (i.e. some skills acquired in the courses are connected to the project activities and can be used during the project and also at the end in other situations)? The second interpretation is proposed in the description of the indicators, but it is not always true, because a mega project that requires high specialisation for each activity cannot in general accept employees with a low level of qualification.

Instead, the first interpretation is interesting and has a meaning that can be shared with several other indicators. The compensations for damage, malfunctions or problems that the construction sites may produce are monetary, but they can also be compensations in terms of human capital creation, cultural capital promotion or local public mobility improvements in sustainable terms. Monitoring these compensation forms is important, and the associated indicators should be specifically coded in relation to this aspect.

The aim of the panel is to constitute a dialogic and transparent tool, and the context indicators should therefore be proposed separately from the others, in order to facilitate the understanding of their roles in the monitoring. The other indicators (sustainability, construction sites and socio-communicative) are explicitly associated with possible actions that should be implemented or risks that should be controlled. However, it would be easier to understand the indicators if they were proposed separately and related to two macro ambits that are different from the original ones:

Difficulties, that is, problems and malfunctions, negative impacts on the local economy or risks for the population, in terms of safety or a lack of services;

Positive traits, that is, promotion of the human and cultural capital; relationship with the territory; information transparency; sustainability communication and governance; economic returns and innovation.

An introduction to the description of the socio-communicative indicators underlines that the list of indicators is not definitive, a direct cause—and effect relationship is not always possible and these indicators, because of their nature, are not suitable for the application of rigid protocols. The first two concepts, that is, of the not definitive nature of the indicator list and of the difficult identification of a direct cause—and effect relationship between the indicators, could be extended to all the indicators. The concept of not being suitable for the application of rigid protocols could be associated more with the difficult acquisition of qualitative data in the Susa valley than to the nature of the indicators.

3.2 How to Evaluate the Negative Impact

A framework was proposed in the document to underline the anomalies in the data trends and evaluate the negative impacts. The Experimental protocol comprises both positive and negative impacts. When the data trends underline a positive impact, it is included in the accountability report, while a negative impact requires surveillance, attention and/or intervention activities. The framework introduces four impact components, which are called criteria: Data trend, Impact duration, Spatial scale of the impact and Probability that the impact will repeat itself. Each criterion is associated with an ordinal scale (see Table 1), and a Significance Index (SI), with a value between 1 and 100, is the result of this formula:

$$SI = (Trend + Duration + Spatial\ scale) * Probability$$

The index is used to distinguish three situations:

- SI >75, substantial impact that requires an urgent and direct intervention,
- $30 \leq$ SI ≤ 75, the impact is only moderate, and an intervention is therefore required, but it is not urgent;
- SI < 30, a mitigation action may be required.

The first and most important point is that the properties of an ordinal scale cannot accept the application of sum and multiplication operations. If the aspects/criteria are significant, a combinatorial approach can facilitate the definition of SI. An example of the procedure steps is synthesised in Tables 2 and 3.

Another point concerns the nature of the criteria. The acquired data trends are data analysis elements that identify an anomaly, and they may suggest the presence of a

Table 1 Adopted scales

Data trend (over at least 3 years)	Impact duration	Spatial scale of the impact	Probability of repetition of the impact
10 Exponential	5 Permanent	5 National	5 Not known
6 Linear	4 Long term (until the end of the project)	4 Regional	4 High
2 Static	3 Medium term (5–10 years)	3 Total valley	3 Medium
0 Insignificant trend	2 Short term (0–5 years)	2 Construction sites and the adjacent municipalities	2 Low
	1 Temporary (days or months)	1 Construction site	1 Improbable

Table 2 The ordinal scale that combines impact duration and probability of repetition

Probability of repetition of the impact Impact duration	Not known	High	Medium	Low	Improbable
Permanent	X	X	X	X	X
LT (end of project)	X	X	X	X	X
MT (5–10 years)	16	16	8	2	1
ST (0–5 years)	12	12	8	2	1
Temporary (days/months)	8	8	4	1	1

Table 3 The ordinal scale that combines impact duration and spatial scale

Spatial scale Impact duration	National	Regional	Total valley	Construction site and adjacent municipalities	Construction site
Permanent	16	14	12	10	7
LT (end of project)	14	12	10	8	4
MT (5–10 years)	12	10	8	6	3
ST (0–5 years)	10	8	6	4	2
Temporary (days or months)	8	6	4	2	1

negative impact, which other elements can then confirm and evaluate in terms of impact strength. The indication "for at least three years of acquisition" as the minimum period of anomaly in the data trends does not seem to be consistent with the fact that an anomaly should be visible in less than 3 years and that the Impact duration may be temporary, and the impact may therefore no longer be evident after 3 years.

When Data trends underline an anomaly, the different functions of the adopted scale express the strength of the anomaly. The proposed formula associates Impact duration and Spatial scale, plus Probability of repetition, to the strength of the anomaly (Data trends) and creates an impact strength index. The use of Data trends as a criterion, and then as an impact component and not as a sign of anomaly, can be risky. The time and spatial dimensions, and the possible repetition of the negative phenomenon may be evaluation aspects/criteria of the negative impact. A formula that synthesises elements of a different nature by means of addition and/or multiplication is in general a risky procedure.

Another point is that the evaluation states of the scales should be analysed in more detail. The Static trend, for instance, can be interpreted as a stable and non-critical anomaly, a stable but critical anomaly or no anomaly is present. A Probability of impact repetition that is Not known is a critical condition, but is no more critical than a High probability. The ordinal scales can be particularly useful, but the definition of each evaluation level should be unambiguous and totally transparent, in order to be (at least sufficiently) objective. In this case, the trend seems objective because it is expressed by an analytical function, but this is not always true, while the definitions of all the other evaluation states may only be objective if explicitly documented (High probability means. . ., Medium means. . . and so on).

3.2.1 Examples of a Combinatorial Approach

Tables 2, 3 and 4 present some examples of ordinal scales that are created explicitly by combining ordinal scales of two or more aspects. The analysts, experts, decision makers and/or any other interested actor should be involved in the analysis.

The example in Table 2 underlines that some combinations are impossible or not significant (X); in this example, this is because a repetition probability is not so informative if the duration states are permanent or until the end of the project. Indeed, the impact repetition after the end of the project is not possible and a permanent impact implies or a control on the possible repetition or a not significant impact worsening. Different combinations can be associated with the same level/ state of the scale; in this example, two different impact durations may have different meanings, in relation to a critical repetition or the same meaning in the other situations, and when the probability is Not known, it may be critical and therefore equivalent to High, thus the states of the scale are identical.

In other cases, all the combinations of states may be possible (see Table 3). Some values of the resulting scale may not be linear, to express that, for example, a negative impact outside the construction site is much more important than when it only occurs within the site. In this example, the two aspects/criteria have the same importance (each passage from one state to another is equal outside the site), but one may be more important than the other, and the values can express this condition.

Table 4 The ordinal scale of a criterion that combines the three aspects

Spatial scale Impact duration and repetition prob.	National	Regional	Total valley	Construction site and adjacent municipalities	Construction site
Permanent	56	44	32	20	10
LT (end of project)	46	36	26	16	8
MT (5–10 years) H	38	30	22	14	7
MT (5–10 years) M	33	26	19	12	6
MT (5–10 years) IM/L	28	22	16	10	5
ST (0–5 years) H	28	22	16	10	5
ST (0–5 years) M	23	18	13	8	4
ST (0–5 years) IM/L	18	14	10	6	3
Temporary (D or M) H	18	14	10	6	3
Temporary (D or M) M	13	10	7	4	2
Temporary (D or M) IM/L	8	6	4	2	1

When only two aspects/criteria have to be combined, the procedure is simple and transparent. When there are more than two, a sequence of combinations is possible. In this example, the valid combinations in Table 2 are inserted into Table 4, where the Probability of repetition of the impact, whenever it may be different, is indicated as H (high, which in Table 2 means between 10 and 16), M (medium, between 5 and 9) or IM/L (improbable or low, between 1 and 4). The scale that results from this combination of states goes from 1 to 56. In real applications, the scale should be created and documented together with the involved actors and/or decision makers. The levels and their number may be different and may be changed during a decision process, for instance when an unexpected phenomenon creates new knowledge or new perceptions of a situation.

3.3 How to Facilitate a Counterfactual Analysis

A counterfactual analysis (Ragin & Sonnett, 2005) was proposed in the document to facilitate the data interpretation. Such an analysis requires a comparison of the data trends pertaining to the Susa valley and to a reference area in order to identify anomalies and then apply the Significance Index, which can facilitate decision making. The document proposes the monitoring of each quantitative indicator in the Susa valley (39 municipalities) and in a homogenous valley, which is considered as a reference for the analysis.

The main problem in the counterfactual analysis is the comparability of the two compared phenomena. In this case, the analysed area in the Susa valley is ample and includes municipalities that are very different from each other, in relation to their local economy and the proximity to the construction sites, and therefore in their involvement in the No TAV movement. The reference area is the Chisone valley, which is in the same Region, but is not involved in the construction of the Trans-European Transport Network, and it includes 14 municipalities, one that is located in both of the valleys.

A multicriteria analysis of these two areas was proposed to generate homogenous and comparable sub-sets of municipalities, which could facilitate the counterfactual analysis.

3.3.1 MC Decision Aid Procedures

Two different procedures are currently being analysed by the interdisciplinary group. Both imply the structuring of a multicriteria model that includes some main aspects, which are made operational by means of certain criteria, that is, analytical functions that assign an evaluation to each municipality in relation to a specific scale.

The relative importance (or weight) of each criterion is an important parameter that has to be included in the MC model. Different weight scenarios can be elaborated to express the points of view and preferences of the involved actors or decision makers. Some procedures facilitate the decision makers in the expression of the weights (see for instance Figueira & Roy, 2002). Moreover, a representation of the structure of the model can facilitate the definition of the weights.

Figure 1 describes how the distribution of the weights (normalised to one) can be defined at the strategic level (Norese & Carbone, 2014) and at the criterion level, where the strategic importance of each aspect is distributed over the criteria, in relation to their different contributions to making the aspect operational.

An MC model includes parameters that have to be defined in relation to the adopted method. In this case, two different analytical approaches can be implemented. Both approaches are possible, and a comparison of their results could facilitate the work.

In the MCDA context, assigning elements (in this case the municipalities) to homogenous groups, classes or categories is a classical decision problem (see Doumpos & Zopounidis, 2002; Zopounidis & Doumpos, 2002). The problem can be distinguished into sorting or nominal problems. When the categories are predefined and ordered, this is a sorting problem, but when no relationship exists between the classes, which are not predefined, this is a nominal classification problem.

ELECTRE Tri is the most frequently used method for sorting problems, while different methods have been proposed in the literature for nominal classification problems (see, for instance, Perny, 1998; Belacel, 2000; Scarelli & Narula, 2000; Norese et al., 2001; De Smet et al., 2012; Fernandez et al., 2010; Costa et al., 2018).

The analysed elements in a sorting problem can be assigned to categories, if they are compared with the components of a reference model, that is, the reference elements that formalise the characteristics of the categories. These elements may be limiting profiles that distinguish and separate the categories, as in ELECTRE Tri B (Roy & Bouyssou, 1993) and ELECTRE Tri-nB (Fernandez et al., 2017), or characteristic actions (which may be called "central actions") for each category, as in ELECTRE Tri-C (Almeida-Dias et al., 2010) and ELECTRE Tri-nC (Almeida-Dias et al., 2012).

The different importance of the criteria is one of the elements that determines the assignment of an element to a category in ELECTRE Tri, by means of fuzzy outranking relations, which are based on the concordance and discordance principles (Roy, 1996). The degrees of credibility of the outranking relations, which result from comparisons of each alternative and the reference actions, i.e. the profiles, are used to assign each alternative to a category, by means of procedures that formally translate decision rules.

The choice of the ELECTRE Tri variants, such as the definition of the weights and the other model parameters, are decisions that can be made and shared in the participative context that generated the model structure and the nature of the criteria, and which validated the evaluations.

The choice of the method for the nominal classification problem is more complicated, but the multicriteria model can be the same for both problems.

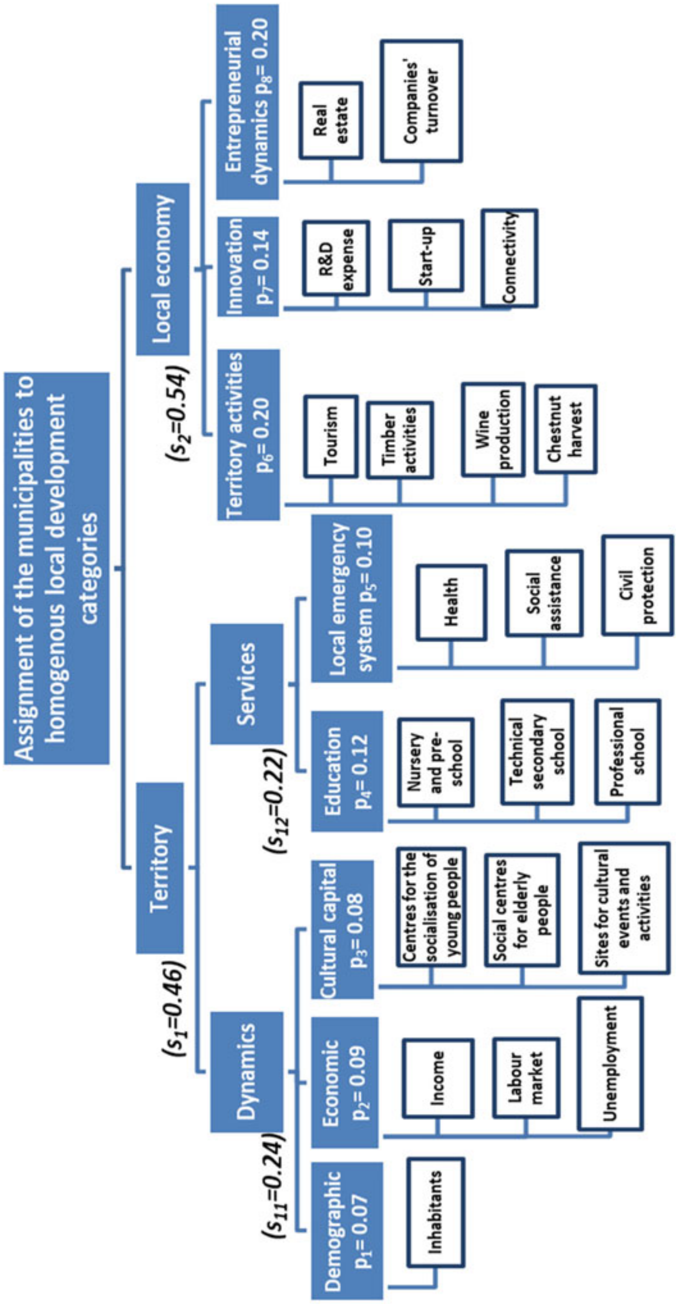

Fig. 1 Structure of the MC model for the application of the ELECTRE Tri method

3.3.2 A Multicriteria Model

The logical structure of an MC model includes the main aspects (or model dimensions) and their analytical formalisation in criteria pertaining to the different related dimensions (Norese, 2016). The model structure is defined in relation to a specific goal (the assignment of the municipalities that present similar characteristics to homogenous local development categories) and includes the main aspects that have to be included. In this case, they are the Dynamics of the territory and its main Services, as shown on the left side of Fig. 1, and the elements that characterise the Local economy, which are shown on the right side.

At this point, the model structure can be oriented to a sorting problem, with the aim of assigning the municipalities to ordered predefined categories. Therefore, the identification of the criteria and their analytical formalisation need an explicit definition of the categories. Such categories may be defined in relation to the economic and territorial organisation of each municipality, which can be Strong and stable (C1), Stable (C2) or with some Weaknesses and instability elements (C3). There are eight possible criteria: demographic dynamics, economic dynamics, cultural capital, education, local emergency system, main activities of the territory, innovation and entrepreneurial dynamics. The main data that can be used to formalise the criteria are listed in Fig. 1 in relation to each criterion.

When the model structure is oriented towards a nominal classification problem, which has the aim of comparing the municipalities and identifying situations of similarity or dissimilarity, the characteristics of each municipality are expressed by attributes. Therefore, a multi-attribute model has to be formalised to be used with a multicriteria nominal classification method. In this case, 22 attributes can be used (see the dark side of Fig. 2).

Both models require the definition of the relative importance of the criteria/attributes. The proposed model structure facilitates the description of this essential concept, which is related to the actors' value system. The values assigned to such parameters have a subjective nature and can only be grasped through communicating with the decision maker(s) in a DA process (Roy & Mousseau, 1996). Some analytical procedures can facilitate this activity (see, for instance, Figueira & Roy, 2002).

The tree structure of the model can facilitate the expression of the strategic importance of each aspect ($s_{i)}$, because a single strategic aspect cannot be much more or much less important than the others. They may have the same strategic importance or even have a different (but not so different) level of importance. The relative importance of the criteria (p_i) can easily be defined, if it is considered a distribution of the importance of a strategic aspect over the associated criteria. An example of how the relative importance of a criterion can be expressed is proposed in Fig. 1.

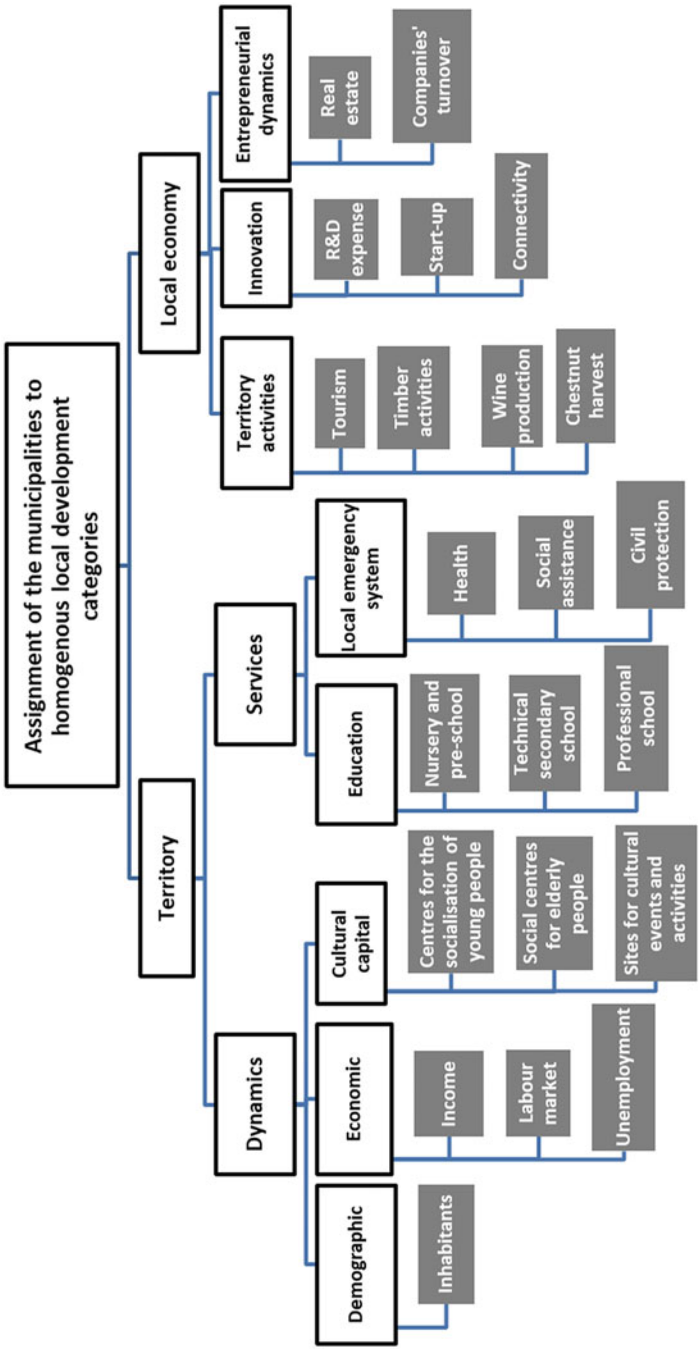

Fig. 2 Structure of the MC model for a nominal classification method

4 Conclusions

The implementation of a monitoring plan for the assessment of impacts on the socio-economic environment generated by a large-scale construction project, or mega-project, is a topic that will become increasingly important in the future. In this chapter, we present the experience of a group of researchers involved in modelling a protocol for the forecasting, control and assessment of the impacts of one of the most important railway corridors in Europe on the socio-economic environment. The protocol includes the study of possible causal links between the construction work and the socio-economic phenomena that have and are taking place in the area under study, for the pre-construction phases (reconstructed through statistical data), during the construction phases and in the post-construction phase. A series of indicators is proposed in the experimental protocol, not only with respect to this study, but also for future occasions of mega-project monitoring. The chapter presents some preliminary reflections on the ongoing pilot study and applications, which may in general be accepted but can sometimes be refused as a result of the monitoring process evolution.

An interesting example pertains to the fact that this mega project requires a high level of specialisation for several activities, but employees can be employed after a well oriented professional preparation. Moreover, some processes are still ongoing to produce these specific qualified figures.

A counterfactual analysis serves to study and compare the dynamics throughout the territories of all those social and economic phenomena that could be influenced or altered by the construction work. This analysis has been proposed in the protocol to specify what kind of manifestation should be considered to predict the severity of a possible impact. The analysis of some socioeconomic phenomena (such as unemployment, the loss of real estate value of buildings, the opening of new companies) has served to understand and describe the trend of societal and economic issues over two territories. A further step will be to conduct a counterfactual analysis on geographical areas that need to be homogeneous in terms of the local development systems. The chapter proposes multicriteria methods and presents two models that will serve to identify different sets of municipalities with similar characteristics in the two territories. The presented models will be tested according to the collected data and the used methods.

In essence, the chapter presents a rather severe criticism of the proposed Significance index and the proposal of a combinatorial procedure to generate the index. It should only be used once it has been ascertained that a certain phenomenon has occurred in a specific area in a totally different way from the rest of the entire valley, or even in municipalities with similar characteristics in another close but different geographical area (in neighbouring geographical areas, such as adjacent valleys).

The proposed reflections on decision aiding are important, because, especially for complex projects that can last 10 years over a vast territory, the management of information complexity is a critical variable for both the political and institutional decision makers. On the other hand, the consideration of different levels of comparison of phenomena and counterfactual thinking is certainly of interest for the development of megaprojects, especially for the impacts that they can generate in the sustainable development field.

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Supporting Sustainable Development Using Multiple Criteria Decision Aid: Towards an Age-Friendly Smart Living Environment

Marina Weck, Iris Humala, Pia Tamminen, and Fernando A. F. Ferreira

Abstract This chapter aims to contribute to a better understanding of how sustainable development (SD) can be supported in the building of age-friendly smart living environments (SLEs) to meet the needs of an increasingly ageing population. The proposed holistic analysis framework enables regional stakeholders engaged in building age-friendly SLEs to analyse the identified conditions and practices facilitating and encouraging knowledge collaboration (KC) and knowledge sharing (KS) that are key determinants of knowledge management (KM) and decisive means in supporting SD. Drawing on multiple criteria decision-aid (MCDA) approach, the framework was developed by involving representatives of regional stakeholders, who are innovation actors of the Häme region's (Finland) quadruple innovation helix model, Quadruple Helix, into a collaborative decision-making process within two empirical studies. The pilot study provided a substantial background for a deeper exploration of multidimensional, complex research questions and context in the main study which utilised problem structuring methods and techniques such as strategic options development and analysis (SODA), cognitive mapping, nominal group technique (NGT), and multi-voting. Assuming a constructivist, process-oriented stance, the main study enabled the development of a more realistic analysis framework through the sharing and aggregating of stakeholders' expertise and experiences and the uncovering of the cause-and-effect relationships among factors related to the topic under study. Taking the form of a collective

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cognitive map, the framework was validated by both the regional stakeholders engaged in the decision-making process of the main study and two external experts, who represented business organisations building age-friendly SLEs. Both studies revealed senior citizens' genuine enthusiasm and motivation to be engaged in building age-friendly SLEs and the vast potential they have in developing collaboration and sharing their knowledge and experience with other stakeholders.

Keywords Sustainable development · Knowledge collaboration · Knowledge sharing · MCDA · Age-friendly SLE

1 Introduction

During recent decades, the changing age structure of the population with the growth in the number of ageing people is a worldwide demographic phenomenon. The rapid growth of the ageing population is observed in the majority of the European countries today. This process is very advanced also in Finland, and the country ranks among the five fastest ageing populations worldwide (United Nations, 2019). The share of seniors aged 65 years or older will increase from the current 20% to 26% by 2030 and to 29% by 2060 (Finnish Institute for Health and Welfare, 2020). The effects of demographic change are already being felt today. Virtually, every country in the world is currently facing common challenges of meeting the needs of ageing people, particularly in the provision of such living environments that enable them to continue living a comfortable, independent, secure and active life outside of any institutional care setting (United Nations, 2019). At the same time, it is expected that older adults and their families will take a more active role in controlling their own well-being and health by interacting with a vast array of digital devices and executing a range of tasks within their home and community. Given the current needs and expectations of relevant parties, digital technology solutions that particularly promote health, well-being and independence are increasingly being found as a promising means of improving the quality of life of seniors (Czaja, 2015; Niehaves & Plattfaut, 2014).

Providing continuous activity and health monitoring, early detection of risk events and cognitive decline, home rehabilitation and physical activity advisors, social connection support, companions for outdoor activities, and many other services not only allow older people to sustain their independence and quality of life in their own homes, but may empower them to participate actively in managing their own health and well-being. The physical space where these services—enabled through the Internet of Things (IoT) and communication technologies—take place is known as the Smart Living Environment (SLE) for ageing well (Alliance for Internet of Things Innovation (AIOTI), 2019). Thus, the SLE for ageing well represents a living environment built by the integration of digital assistive technologies within the services requested by older adults for supporting health and well-being and extending independent living in their own homes as well as responding to the needs and expectations of the social welfare and healthcare sector. However, in Finland, one of the biggest current challenges is to build age-friendly SLEs that are integrated into the infrastructural (built environment), technical, financial, administrative and social network producing community-driven and customer-oriented services (Topo, 2015; Kurkela et al., 2017). Although Finland's government promotes the piloting of and experimentation with innovative solutions and the scaling up of successful experiments in all public services, there is a strong need for seamless and committed knowledge collaboration between all stakeholders—business, academia, society and government organisations—to make it possible to provide better products and services for improving the health and well-being of the community (Holopainen et al., 2018). Collaboration is critical particularly between the elder care system, technology producers and senior citizens to support the positive attitudes of the latter towards technology and its acceptance as well as the quicker uptake of innovative solutions (Weck et al., 2020).

Addressing the challenges of building age-friendly SLEs reflects the United Nation's Sustainable Development Goal (SDG) 11 'Make cities and human settlements inclusive, safe, resilient and sustainable', which stated in the 2030 Agenda for Sustainable Development (Agenda 2030) (United Nations, 2015). To support SD to meet the needs of urban development, local or regional governments are recommended to adopt integrated, multi-sectoral approaches to address sustainable urban development from a holistic perspective, ensure transparency, enable the role and engagement of citizens in planning by creating engagement mechanisms and opportunities, as well as participatory practices that can lead to collaborative governance, and foster opportunities and mobilise successful examples, such as citizens' bottom-up initiatives for sustainability (Sulla et al., 2020). Furthermore, the recent report of Organisation for Economic Co-operation and Development (OECD) provides action-oriented recommendations to guide policy makers to implement a territorial approach to the SDGs, for example: *"use the SDGs to address concrete local challenges"* and *"use the SDGs as a vehicle to enhance accountability and transparency through engaging all territorial stakeholders, including civil society, citizens, youth, academia and private companies, in the policy-making process"* (OECD, 2020, p. 21).

Importantly, the Agenda 2030 which aims to set the world on a path to transform the world towards sustainable development (Pisano et al., 2015; Baker, 2016; Assunção et al., 2020) calls specifically for enhancing "knowledge sharing" in sectors contributing to the achievement of the SDGs, and for cities and regions, this means that robust knowledge sharing (KS) among all regional stakeholders can be a driver for achieving SDG 11. In practice, none of these stakeholders can achieve SDGs in isolation without collaboration and the sharing of knowledge learned through their development work and experience in solving joint challenges. Through KS practice, stakeholders can contribute to knowledge application and innovation (Wang & Noe, 2010) and minimise inefficient efforts and the wasting of scarce resources.

The Covid-19 pandemic has slowed down the progress of reaching the goals set in the 2030 Agenda for Sustainable Development (United Nations, 2021a). António

Guterres, Secretary-General of the United Nations, states in the latest SDG report (ibid.) that the recovery of the global pandemic requires collective action for collaboration based on sound data and science to create more inclusive and equitable societies, which emphasises the essential role of well-functioning and robust knowledge management (KM) models even more. Therefore, collaboration and KS are perhaps the most essential means for promoting sustainable development to meet the needs of age-friendly SLEs.

In this study, collaboration that aims to advance synergies between all stakeholders' activities in building age-friendly SLEs and an exchange of knowledge and ideas on the most prominent research achievements and development challenges is viewed as knowledge collaboration (KC). In relation to KC, knowledge sharing (KS) is of increasing importance, and it means a practice through which the mutual exchange of stakeholders' knowledge, skills and experiences take place. Despite the widely acknowledged view that KS and KC are key determinants of KM and decisive means in supporting SD, the body of empirical research attempting to provide evidence on how KC and KS practices can be improved is inadequate. Recognising the importance of supporting SD to meet the needs of senior citizens for the age-friendly SLEs, the focus of this study lies on KC and KS between all regional stakeholders engaged in building age-friendly SLEs. From the perspective of practitioners and researchers, it is essential to support the regional stakeholders' self-assessment and decision making in facilitating KC and KS that foster the emergence of ground-breaking ideas, concepts and scenarios leading to sustainable and innovative products and services while building age-friendly SLEs.

Thus, the general aim of this study is to contribute to a better understanding of how KM can be improved in order to support SD and meet the needs of senior citizens with regard to age-friendly SLEs. In particular, the study sought to determine conditions and practices that facilitate and encourage KC and KS between all regional stakeholders engaged in building age-friendly SLEs. Additionally, a specific emphasis was placed on the engagement and contribution of senior citizens.

The research questions were investigated in the context of the Häme region, Finland, where regional stakeholders collaborate with the aid of the OSIRIS Interreg BSR project to address emerging challenges in meeting the needs of senior citizens for age-friendly SLEs as well as to advance the achievement of the 2030 Agenda for Sustainable Development. These regional stakeholders represent innovation actors of the quadruple innovation helix model, Quadruple Helix (QH), which is a concept emphasising broad collaboration in innovation between government, academia, industry, and civil society (Arnkil et al., 2010). They play different roles from the regional policy-makers and managing authorities, public and private service providers in social welfare and healthcare, research and business organisations, to financers and associations of senior citizens or end users.

From the methodological perspective, this study exemplifies a constructivist, process-oriented approach (Belton & Stewart, 2002; Bell & Morse, 2013), allowing the combination of quantitative and qualitative methods and techniques such as cognitive mapping, nominal group technique (NGT) and multi-voting for problem identification, solution generation, and decision making. Cognitive mapping is particularly useful to enable multiple decision makers (i.e. regional stakeholders) to be brought together, contribute their diverse knowledge and expertise to approaching multidimensional research questions and the underlying complexity of decision contexts by representing the situation in a structured and visualised manner (Eden, 2004; Eden & Ackermann, 2004). In this study context, the literature reports no prior research on this methodological combination.

The structure of this chapter comprises the following sections. The next section discusses literature focused on sustainable development, end-user engagement, and the role of KM. Then, the methodological background is introduced. Section 4 describes the procedures and decision-making process to determine and structure complex issues that concern the problem at hand within the two studies. Section 5 presents the results of the main study and the section concludes with the discussion of limitations, theoretical implications and contributions to managerial practice.

2 Sustainable Development and Knowledge Management

In the Brundtland report (United Nations, 1987), SD has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development, a set of 17 sustainable development goals (SDGs), which set out a 15-year plan to achieve the goals. Implementing the SDGs that address global challenges aims to build a better future for all people (United Nations, 2015). Thus, for example, the aim of SDG 11 'Make cities and human settlements inclusive, safe, resilient and sustainable' is to renew and plan cities and other human settlements to provide opportunities for all, with access to basic services, energy, housing, transportation and green public spaces, while reducing resource use and environmental impact (Eurostat, 2021). SDG 11 connects to SLEs and senior citizens through its targets, which addresses such issues as supporting positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning, as well as the needs of those in vulnerable situations, such as senior citizens (Global Goals, 2021).

As sustainable development is meant to be the ultimate and most important global commitment for societies this century, it addresses environmental, economic and social aspects (United Nations, 1987; Giddings et al., 2002) such as conditions towards improvements in the quality of life for all age segments of the population. Accordingly, SD is also about maintaining senior citizens' activity and health, and developing effective solutions for ageing at home that are related to the design of the living environment (Grazuleviciute-Vileniske et al., 2020) and age-friendly SLEs alike. Enhanced by digital assistive technologies integrated within the system of health and well-being services, SLEs can enable senior citizens to live more actively and independently in their own hommes. There is already a range of digital devices and service solutions available on the market to help achieve this. Moreover, they are being widely used by ageing people for different types of healthcare and social support services (cf. Morris et al., 2013).

Building an SLE is often viewed as a solution to societal problems and a common target of governments and businesses worldwide enabling seniors to continue living a comfortable, independent and active life outside of any institutional care settings (Weck et al., 2020). According to Trivellato (2017), building SLEs relates particularly to social sustainability, defined by McKenzie (2004, pp. 15–18) as a "*positive condition marked by a strong sense of social cohesion, and equity of access to key services (including health, education, transport, housing and recreation).* [. . .] *Social sustainability occurs when the formal and informal processes, systems, structures and relationships actively support the capacity of current and future generations to create healthy and liveable communities*". Furthermore, Parjanen et al. (2018) highlight the essential role of socially sustainable innovation processes in building more sustainable communities worldwide. They claim that instead of focusing on the end result, the focus should be placed on socially sustainable innovation processes that are the processes of innovating supported by an open and interactive development approach, resident and user-driven involvement, communication, learning and feedback, and impact assessment.

In the regional level, the paragraph 80 of the United Nations' Agenda 2030 (United Nations, 2015) highlights the importance of peer learning, through voluntary reviews, the sharing of best practices and discussion on shared targets, and welcomes the cooperation of regional and subregional commissions and organisations. Local and regional governments are thus asked to advance the mobilisation of a wide range of stakeholders, facilitating "bottom-up" and inclusive processes, and forming multi-stakeholder partnerships (United Nations, 2021b). Further, paragraph 89 (United Nations, 2015) calls on major groups and other stakeholders, including local authorities, to report on their contribution to the implementation of the Agenda. With that, United Nation's Agenda 2030 closely connects to the Quadruple Helix (QH) innovation framework. In the QH approach, it is the users or citizens who own and drive the innovation processes (Carayannis et al., 2015) by participating in the actual development work as well as proposing new types of innovations, which connect them with other stakeholders (Arnkil et al., 2010).

In building age-friendly SLEs, it is the senior citizens who represent the key "bottom-up" end-users.

The role of senior citizens in SD and building SLEs is crucial, because through offering versatile living experiences, information and expectations and participating actively in decision making, they contribute both issues that can affect them and their communities (cf. Tamminen, 2016; Tuckett et al., 2018). In addition, end-users engaged in innovation processes benefit from a reflective approach, because they are engaged in an innovation process that fits into their everyday practices, as well as being able to reflect on their own knowledge creation and learning from their involvement (Ståhlbröst & Holst, 2017).

Knowledge is "*the most strategic resource*" (Roth, 2003, p. 32) and essential capital (Davenport & Prusak, 1998). It "*consists of information and know-how*" (Schrettle et al., 2014, p. 79), it is acquired from lessons learned together with new ideas and concepts (UN, 2016), and is in the heart of sustainable development decision-making. Knowledge is an essential source of innovative initiatives and a key driver and indispensable prerequisite for the sustainable development of societies and directly associated with SDGs (Brandner & Cummings, 2017; Knowledge for Development Partnership, 2017, p. 1), as it is stated by Van Kerkhoff (2013, p. 82) "*sustainable development is a knowledge intensive process, but plagued by persistent concerns over our apparent inability to connect what we know with more sustainable practices and outcomes*". Therefore, it is imperative to integrate the practices of knowledge management with the aforementioned socially sustainable innovation processes, while these processes not only depend on the availability of knowledge, but on the collaboration and KS across and between various regional stakeholders advocating for Agenda 2030.

KM is widely acknowledged as the most critical means for achieving SDGs (United Nations, 2016; Ulewicz & Blaskova, 2018; Mikalauskiene & Atkociuniene, 2019). Bounfour (2003) defines KM as a set of procedures, infrastructures, managerial and technical tools, needed for creating, sharing and leveraging information and knowledge. Adopting KM allows synergies, cross-fertilisation, bottom-up and top-down, horizontal and vertical learning and sharing (Brandner & Cummings, 2017). The United Nations (2016) underlined the importance of KM that can be used as a tool for promoting collaboration, improving access to knowledge, bringing together the inputs of the various stakeholders involved in SD activities. KM can be achieved "*through promoting the creation, sharing and application of knowledge as well as through the feeding of valuable lessons learned and best practices into corporate memory*" (ibid., p. 55).

Furthermore, to attain the United Nations' Agenda 2030, the world must recognise the substantial need to embracing the culture of knowledge sharing across boundaries without barriers. The importance of cooperation and knowledge sharing in sustainable knowledge communities utilising accumulative knowledge has been highlighted by Mikalauskiene and Atkociuniene (2019). According to them, "*the sustainability in the context of knowledge management means the precise conversion of economic goals into knowledge goals, refusal of outdated knowledge, identification and maintenance of useful knowledge, preservation of people who have valuable knowledge, knowledge usage in infrastructures, unexpressed (implied) knowledge transformation into expressed concepts and models, encouragement of knowledge sharing*" (ibid., p. 151).

In this study, KC means an activity that aims to advance synergies between people and an honest exchange of knowledge and ideas on outstanding research achievements and development topics (Wang & Noe, 2010; Faraj et al., 2011). Knowledge collaboration and communication are closely related to building healthy knowledge ecosystems, as well as knowledge partnerships, which include different kinds of knowledge processes, such as knowledge sharing, peer learning, co-creation and innovation, application and preservation (Knowledge for Development Partnership, 2017). In the context of urban and regional development, strong, open and transparent local knowledge partnerships, contributing to the achievement of the SDGs, have been seen vital to the validation and localisation of global knowledge resources and approaches and helping knowledge exchange to be realistic, pragmatic, and anchored in local knowledge ecosystems (institutions, markets, cultures) (Knowledge for Development Partnership, 2017).

Against this background, in the context of developing age-friendly SLEs, knowledge collaboration and knowledge sharing, as key determinants of KM, can be regarded as essential elements to achieve progress towards achieving SDG 11 and a balance between the three sustainability pillars—environmental protection, economic development and social cohesion (UN, 1987; Giddings et al., 2002).

3 Multiple Criteria Decision Aid

To understand how KM practices can be improved in order to support SD and meet the needs of senior citizens with regard to age-friendly SLEs, there is a need for a holistic analysis framework of factors indicating conditions and practices that facilitate and encourage KC and KS between all regional stakeholders and improve their decision making. Given this complex research problem and its context, structuring complex decision problems well and considering multiple criteria explicitly in decision making lead to more accurate and better-informed decisions (Belton & Stewart, 2002). Thus, in this research, when complex factors are necessary to be considered in order to select favourable alternatives, employing multicriteria decision analysis/aid (MCDA) approaches is pivotal. The diversity of MCDA methods and techniques necessitates reflection on the most appropriate method for the decision context at hand (Roy & Slowinski, 2013).

This research possesses many similar characteristics with those for which problem structuring methods (PSMs) have been developed (Rosenhead & Mingers, 2001; Mingers & Rosenhead, 2004). PSMs are flexible mechanisms for addressing complex problems and providing a richer view of the decision situation by representing it in a structured model for decision-making in developing innovative solutions (Mingers & Rosenhead, 2004). They are particularly useful to enable effective support in different phases of the decision-making process when there is a need to address complex issues characterised by the presence of multiple actors, who often possess different perspectives and objectives, and even conflicting interests and uncertainties (Rosenhead & Mingers, 2001; Mingers & Rosenhead, 2004). The literature provides a range of PSMs (Mingers & Rosenhead, 2004) including, for example, the most well-known strategic options development and analysis (SODA) initially developed in the 1980s by Eden et al. (1983). Providing a means for managing process and content (Ackermann & Eden, 2010), "*Strategic options development and analysis (SODA) is a general problem identification method that uses cognitive mapping as a modelling device for eliciting and recording individuals' views of a problem situation*" (Mingers & Rosenhead, 2004, p. 532).

Being an integral part of the SODA methodology, cognitive mapping is commonly used to identify ideas and structure the thinking of various decision makers with their own problem (Eden, 1988). Cognitive mapping facilitates the collective sensemaking and the structuring of complex decision problems in an easily understood way by supporting communication and stimulating mental associations (Ackermann & Eden, 2001; Kang et al., 2012; Gavrilova et al., 2013; Castanho et al., 2019). Cognitive mapping thus can help individuals and groups to explore more systematically and thoroughly decision problems, and cognitive maps are visual representation tools used to assist decision-making processes. According to Ackermann and Eden (2010, p. 138) "*'cognitive map' is a model of the 'system of concepts (or statements) used by a person to communicate the nature of the situation—the way they make sense of their world'*", and Eden (2004, p. 673) defined it as "*the representation of thinking about a problem that follows from the process of mapping*".

4 Methodological Application

The decision-making process to determine highly complex issues that concern conditions and practices facilitating KC and KS was conducted in two studies: (1) a pilot study; and (2) a main study, the latter being divided into two phases. Both studies involved representatives of the QH regional innovation actors of the Häme region. Data collection procedures of both studies were implemented in December 2019 at the premises of the Hämeenlinna University Centre of Häme University of Applied Sciences within the framework of OSIRIS Interreg BSR project.

4.1 Pilot Study

The pilot study consisted of a focus group workshop, which acted as the introduction to the main research and allowed the collection of high-quality data in a social context and an understanding of the research problem from the participants' perspective (Patton, 2002; Kim, 2010). Twelve regional innovation actors or QH representatives of academia, industry, government, and civil society participated in the workshop. Three researchers adopted the role of "facilitator" and facilitated the participants' discussions in two focus groups that enabled open communication and promoted collaborative decision making and learning among the participants in "*a more natural environment than that of individual interview because participants are influencing and influenced by others—just as they are in real life*" (Casey & Kueger, 2000, p. 11).

The aims were to provide a forum for open discussion and to establish an initial understanding of the questions and complex context of the research as well as identify the key regional innovation actors who are directly engaged in building age-friendly SLEs in the Häme region. The brainstorming method was utilised in a relaxed and informal manner that encouraged people to express their thoughts freely

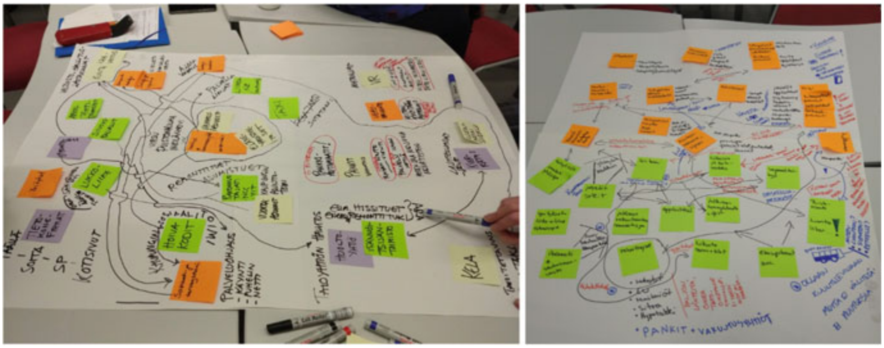

Fig. 1 Knowledge visualisation work results of two focus groups

and generate creative ideas. Working in two groups, workshop participants were asked by three facilitators to express jointly their knowledge about key innovation actors who are and should be engaged in building age-friendly SLEs in the region and KC and KS with easy drawings of schemes. The knowledge visualisation results of two groups are presented in Fig. 1.

The results of both groups' discussions increased awareness of the key regional innovation actors directly engaged in building age-friendly SLEs and the significant role senior citizens play in supporting KM practices as the committed and enthusiastic QH representatives of regional innovation actors. In addition, the researchers' comprehension of the research complex context improved significantly. A short summary of the obtained results is introduced in Table 1. The pilot study thus offered a substantial background that assisted the researchers in proceeding with a deeper exploration of research questions by applying the structuring methods and techniques in the main study.

4.2 Main Study: Cognitive Mapping and Problem Structuring

The main study was carried out in two phases: (1) knowledge panel meetings; and (2) external validation sessions. The aim of the first phase was to bring together knowledgeable experts who represented QH regional innovation actors actively engaged and shared a broad understanding of the problems and concerns related to the building of age-friendly SLEs in the region. In the selection of the members for the two panel meetings, considerable emphasis was put on their heterogeneity in terms of professional expertise, which was accomplished by using the QH approach, and gender. However, the purpose of the expert selection was not to achieve representativeness (Bell & Morse, 2013; Ormerod, 2020) but to collaborate effectively and produce well-focused results while approaching multidimensional research questions with the underlying complexity of contexts. Following the

Table 1 Summary of the results of the two focus groups

Key regional innovation actors	Senior citizens' engagement and needs
Companies and private services (architects, ICT, household appliances, security, taxi, maintenance and repair, real estate management, services centres)	Advice on the spot; appliance and operational safety; fire safety; applying financial support to renovations, elevators etc.
Financial services organisations	Assistance in money withdrawal and deposits; face-to-face personal service; information about different services available
Cities & municipalities	Supporting clinics for seniors (e.g., ICT support, peer support); traffic services, recreational activities, appointments to health services, electronic social services
Public transport providers	Assistance for choosing routes and timetables, waiting times, purchase of tickets, group tickets, personal service, accessibility, call services, carpooling, proactive traffic planning, encouraging to use public transport services
Real estate developers and construction companies	Participating in development of public premises (e.g., meeting rooms and gardens) for the opportunities to meet different generations; community housing; age-friendly construction
Condominiums and their boards	Providing support to renovations and recycling solutions
Social insurance institution of Finland (KELA) and tax authorities	Providing support for personal services; accessibility support
Education institutions	Collaboration with student projects; social media training activities
Voluntary organisations (senior citizens' associations and other social networks: Family, friends, neighbours) and parishes	Collaboration with cities & municipalities, parishes, and many regional innovation actors; voluntary work

suggestion made by Eden and Ackermann (2001, p. 22) (i.e. "*the consultant* [i.e. the researcher or facilitator] *will relate personally to a small number (say, three to ten persons)*" or "*small groups (ideally of 6–10 key individuals)*" (Eden & Ackermann, 2004, p. 618)), a group of eight experts or panel members were recruited with an important condition for them to commit to participating in the whole decision-making process of the two knowledge panel meetings. Thus, during this phase, eight selected experts acted as decision makers representing researchers, product and service developers, financers, and the local authorities involved in regional economic and business development, as well as the region's senior citizens' associations. Both panel meetings were process-oriented in nature and facilitated by one main facilitator or instructor and two assistants, each one lasting 4 h.

During the first knowledge panel meeting, experts focused on how KM can be supported among the regional innovation actors. In practice, the panel members were given the challenge of determining conditions and practices that facilitate and encourage KC and KS, as well as benefits and barriers. The general aim was to

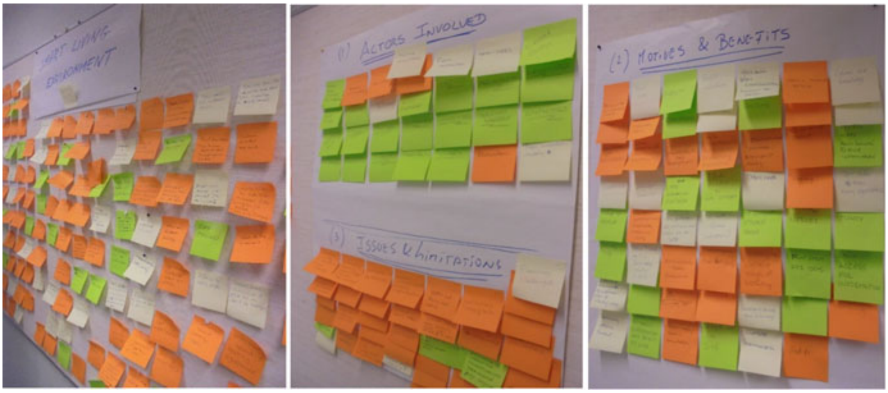

Fig. 2 Post-it notes representing identified criteria and respective clusters

create a collective cognitive map that sought to represent the researched complex issues through cause-and-effect relationships (Ackermann & Eden, 2001; Silva et al., 2021), and therefore the following trigger question was introduced: "*Based on your values and personal experience, how do you describe the 'best' way to support KM?*"

The SODA method (Eden & Ackermann, 2001) was applied to support collaborative decision making and enable all the decision makers to structure the problem during the panel meeting. The method assisted the process of making sense of the problem, identifying key goals, stakeholders, concerns, uncertainties, and so on, ensuring that each panel member had a clear understanding of the problem's context and overall structure (Belton & Stewart, 2002), and could express their opinions from their own perspective. They generated and wrote down 331 ideas or decision criteria with the help of the "*post-its technique*" (Eden & Ackermann, 2001), using one post-it note for each criterion that were placed on a whiteboard by two panel assistants. The next task was to organise criteria by key areas of interest, thereby defining the central criteria clusters, identifying criteria that impact on KM and marking them by a minus sign (−) on their post-it notes whenever a negative cause-and-effect was identified. Figure 2 presents a few snapshots of the panel meeting results.

The panel members identified and labelled six clusters, namely: (1) *Involved Innovation Actors*; (2) *Motives and Benefits*; (3) *Barriers, Issues and Limitations*; (4) *Improvement Actions and Initiatives*; (5) *General Skills, Capabilities, and Competences*; and (6) *Resources and Knowledge-based Activities*. Their final task consisted of creating a hierarchy of all the identified criteria within each cluster that means the organising of ideas on post-it notes by order of importance on the whiteboard, i.e. from top—the most important—to bottom—the least important. This was followed by discussions regarding the most fundamental characteristics of age-friendly SLEs. Three strategic determinants were identified: "*Comfortable Life*"; "*Active Life*"; and "*Independent Life*".

This visual representation of results on the whiteboard (see Fig. 2) was particularly helpful for the following tasks in the decision-making process, because it required the full engagement of decision makers in structuring the problem at hand and generating a multiple criteria framework for the collective cognitive map. Once the basic structure of the framework was finalised and the first panel meeting was closed, the collective cognitive map was developed using the *Decision Explorer* software (www.banxia.com). Figure 3 introduces the collective cognitive map, which contains all 331 identified criteria or determinants. The cause-and-effect relationships between identified criteria/determinants are shown by the arrows. Due to space limitations in this book chapter, it is not possible to present a clearer version of the map, but the general structure is visible. A larger version of the map is available upon request from the corresponding author.

The same group of eight decision makers participated in the knowledge panel meeting II. This meeting was dedicated to the validation of the developed collective cognitive map through analysis, discussion, and revision. The developed collective cognitive map was introduced to the experts, and they were invited to amend the map's content (i.e. all criteria) and/or shape, if changes were considered to be essential and necessary. Figure 3 displays the final or validated version of the cognitive map. While the development process of this map was particularly comprehensive in terms of knowledge and experience exchange, it was intrinsically subjective. Different maps could be structured by other experts and during longer time, for example. Therefore, it should be noted that "*there is less emphasis on the outputs per se and more focus on process: how the group members interact and what they learn about themselves from that interaction*" (Bell & Morse, 2013, p. 962).

Additionally, the second panel meeting consisted of the focus group discussion with a specific emphasis on the contribution of senior citizens. NGT and multi-voting were applied as structuring methods to obtain inputs from the experts, promote their active participation in the decision-making process, and facilitate the identification of common ground from different perspectives. Each panel member had the opportunity to present and defend his/her answer to the trigger question for 15 min. The trigger question in this second meeting was as follows: "*Based on your values and personal experience, how can senior citizens contribute to KC and KS among regional innovation actors?*". No discussion was allowed during this 15-min period to avoid interruptions and guarantee equal expression opportunities to each member. After the 15-min period given to each panel group member, their answers were written on a vertical white board visible to everyone. An active group discussion took place at this moment to validate the individual answers obtained. In total, 21 initiatives and actions were suggested. Then, multi-voting was utilised in order to gain a ranking of scores assigned to senior citizens' initiatives and practices that can contribute to the KC and KS among regional innovation actors building age-friendly SLEs (see Table 3 in Sect. 5).

The aim of the second phase of the main study was to validate the developed visual representation of consolidated results, i.e. collective cognitive map. Two interviews were held with external experts from two Finnish private business organisations from the Häme and Lapland regions of Finland, both directly engaged

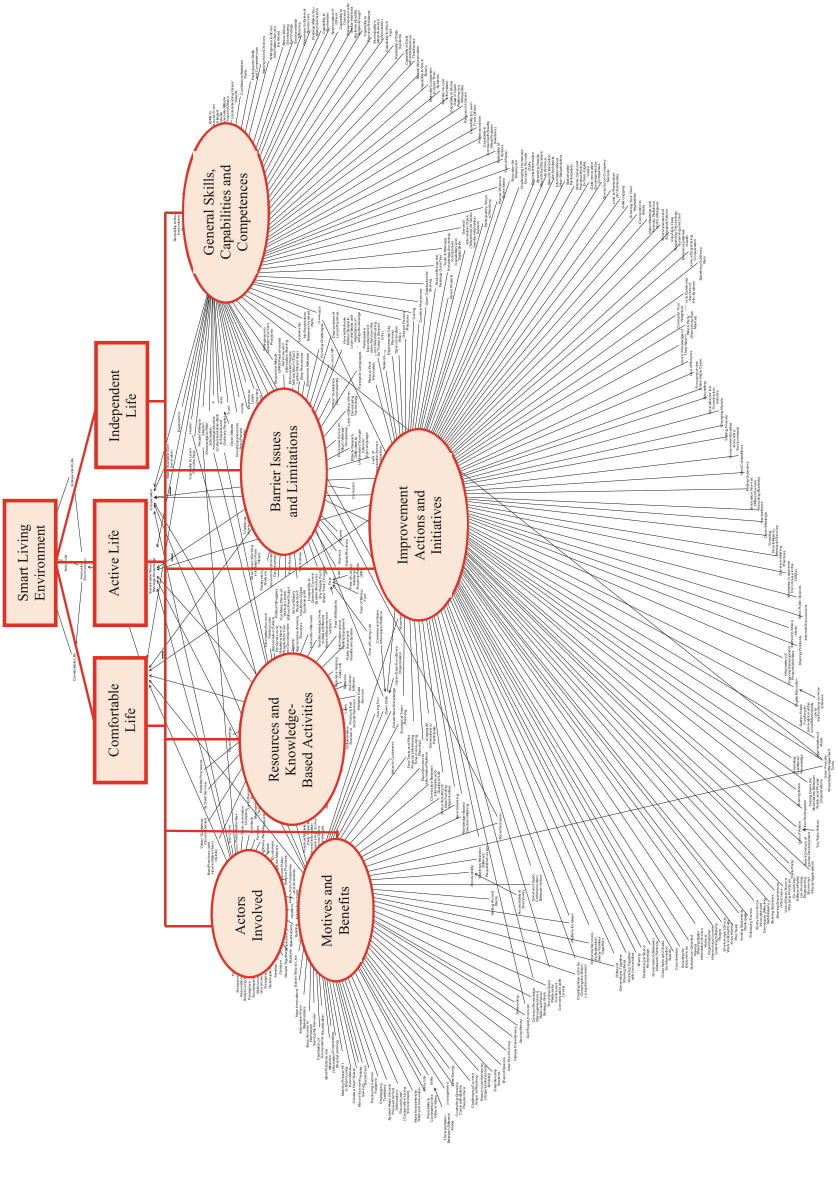

Fig. 3 Collective cognitive map

in building age-friendly SLEs. Having presented the results to the interviewees, the interview discussions focused on the following issues: (1) the comprehensiveness of the determined factors in the visual framework or cognitive map; (2) the representativeness of key groups of QH innovation actors or experts engaged in building age-friendly SLEs; (3) the transferability and generalisation of the results; and (4) the usefulness of the results' visualisation in future decision-making processes. Both interviews lasted for approximately 1 h, audio video recorded and transcribed verbatim.

In the discussion about the framework comprehensiveness, both interviewees provided positive feedback, which is evidently reflected in the following interview quotation: "*The analysis is extremely comprehensive in relation to the time and resources available, and it definitely covers all viewpoints* [...] *One just cannot say that anything would have been left out*" (citing one of the respondents). Then, having been familiarised with the list of experts and their organisations who participated in the first two stages of the main study, the interviewees considered that the experts involved in the decision making and framework development work were competent and qualified, and represented the relevant organisations from academia, business, policymakers, and civil society or senior citizens' associations in accordance with the QH approach. Both interviewees were consistent in their point of view, saying that the experts were therefore able to generate heterogeneous ideas making a valuable contribution to decision making based on their diverse experience and expertise in the problems under analysis. One of the respondents described the representativeness as follows: "*All in all, there is a good representation of experts covering different fields, aspects, and viewpoints*". The next issue concerned the generalisation and transferability of the results, and in the words of one of the interviewees: "*the findings are global and fully transferable at least in Nordic countries, which have rather similar cultures. In my opinion, a comfortable, active and independent life is the most important issue worldwide* [in terms of age-friendly SLEs]". In addition, the other respondent highlighted "*the development level of the society that probably also determines and influences* [the transferability and generalisation of the results]". Finally, both interviewees had rather similar opinions regarding the usefulness of visual representation of decision-making results, because it permits any practitioner to see very complex issues in one "*big picture*". The visual representation *"brings out the motivators which make people act and where to they want to proceed, and guide to make decisions serving as many people as possible [...] and especially by zooming the visual map, also single issues can be distinguished and [the visualisation] becomes more beneficial and available*" (citing one of the respondents).

Overall, the results of this phase support a conclusion that data consolidated in the cognitive map are valuable and directly applicable by practitioners engaged in building age-friendly SLEs. However, the idiosyncratic results cannot be generalised for other contexts (e.g., regions) without the necessary adjustments. Importantly, these interviewees did not participate in the two knowledge panel meetings with the QH representatives of regional innovation actors, and therefore, they were impartial reviewers of the study process and the results.

5 Results Analysis and Discussion

As it is recommended for sustainability researchers, the adopted methodology allowed to focus more attention on stakeholder participation (Olawumi & Chan, 2018). Representatives of the key QH regional stakeholders identified in the pilot study took an active role and participated as experts in the decision-making process in both knowledge panel meetings of the main study. The cognitive mapping technique combined with the SODA method enabled them to share and aggregate their opinions and experiences, and identify a total of 331 determinants or criteria of conditions and practices that facilitate and encourage KC and KS between all regional stakeholders engaged in building age-friendly SLEs. This technique permitted to create a holistic framework with cause-and-effect relationships between these criteria. The multi-criteria framework or collective cognitive map (see Fig. 3) can support decision making in promoting sustainable development through KC and KS. The created six groups of criteria or clusters, their sizes, and examples of identified criteria (i.e. conditions and practices that facilitate and encourage KC and KS) are shown in Table 2, starting from the largest to the smallest cluster.

The size of the clusters indicates how many criteria are integrated into each cluster, and basically, it refers to the significance within the framework structure. The number of clusters and their sizes depict the complexity of the decision problem at hand.

In the created hierarchical structure, the largest group of criteria *Improvement Actions and Initiatives* is directly related to the main research question and suggest 93 identified conditions and practices that facilitate and encourage KC and KS to promote sustainable development in meeting the needs of senior citizens with regard to age-friendly SLEs. The next two largest groups *General Skills, Capabilities, and Competences* (in total, 61 criteria) followed by the *Motives and Benefits* cluster (in total, 59 criteria) were found to be closely connected with *Improvement Actions and Initiatives*, and may have a considerable impact on sustainable development in the region. The next largest *Barriers and Limitations* cluster with 54 criteria was determined as critical because these factors raised a lot of concern regarding the negative impact they may have on the criteria of all other clusters that are positive for sustainable development. The following clusters *Resources and Knowledge-Based Activities* and *Involved Innovation Actors*, with 33 and 31 criteria respectively, are at the core of the structure, and these identified criteria play a central role in screening and accelerating the uptake of innovative products and services for building age-friendly SLEs and cover various resources that fundamental to the effective KM implementation. Additionally, among the strategic criteria emphasised by the expert group, the criteria such as "*Comfortable Life*", "*Active Life*", and "*Independent Life*" were incorporated into the structure. These strategic criteria, corresponding to the meaningful characteristics of the age-friendly SLEs, were regarded as a common target of sustainable development for QH regional stakeholders, and therefore placed at the top above all the other criteria.

Table 2 Clusters, their sizes, and examples of identified criteria

Cluster/group of criteria	Size	Identified criteria/determinants (examples)
Improvement actions and initiatives	93	Working with universities; inviting students to participate; listening to elderly people; sharing experiences of success; meetings with end users; sharing problems; sharing solutions; informal discussions; storytelling; idea competitions; pilot tests; participatory ways of working; encouraging all generations to participate; publishing to share knowledge; clear aims and goals for information needs; etc.
General skills, capabilities, and competences	61	Understanding users' needs; appreciated attitude towards others; open attitude; willingness to share; willingness to listen; willingness to question current practices; willingness to interact; capability to resolve problems; capability to address meaningful issues; receptivity to innovations; trust; reliability of actors; ability to filter information; etc.
Motives and benefits	59	Good and open communication between actors; easy access to information; controlling growing costs of the care of elderly people equal access to information platform; new era of living; easy life; climate friendliness; accessibility to everybody; social care; shared spaces; etc.
Barriers and limitations	54	50% of elderly people do not use/know any digital systems at all; incapability to question current system structures; political struggles; funding challenges; fear of mistakes; prejudices; lack of communication across organisations; underestimation of local practices; dismissive attitudes; etc.
Resources and knowledge-based activities	33	Technology for sharing; best practices; management models; testing labs; access to creative spaces; collaborative research; planned information channels; tacit knowledge; reliable data sources; reliable processes; instruction manuals; publications; reporting systems; laws; etc.
Involved innovation actors	31	Public authorities; private and public service providers; building constructors; end-users; elderly people; researchers; designers; students; families; third sector; etc.

The final analysis focused on the engagement of the end-user or senior citizens' group of QH regional stakeholders in the activities that contribute to KC and KS and lead to better decisions supporting sustainable development in the region. Table 3 depicts a list of the engagement initiatives and actions that were proposed and prioritised according to the voting results of the experts participating in the panel meetings.

The findings showed that having accumulated both vast professional and personal experience, and with more time at their disposal, senior citizens represented very motivated and enthusiastic actors willing to be engaged in age-friendly SLE-related decision-making. The critical role of this group of stakeholders is confirmed by 21 well-focused engagement initiatives and actions through which senior citizens can contribute to the KC and KS in practice. These findings corroborate many different ways and levels of achievement successful stakeholder engagement

Table 3 List of the engagement initiatives and actions after the ranking of measures

	Engagement initiatives and actions		Engagement initiatives and actions
1	Taking part in the city planning	12	Participating in digitalisation as an active learner
2	Joining open discussion groups for end-users	13	Improving digital skills
3	Sharing ideas in the open innovation platforms	14	Providing “neighbourly” help
4	Interpreting the needs of “digi-passive” senior citizens	15	Allowing access to senior citizens’ personal data (medical data, etc.)
5	Supporting usability/user-centred design of products and services for senior citizens	16	Supporting easy way to get help for senior citizens
6	Supporting senior citizens to participate in pilot projects	17	Learning new methods of teaching and learning
7	Participating in innovation development activities	18	Accepting of innovative home-based services
8	Participating in decision making as an innovator	19	Joining discussion groups in senior associations
9	Gathering soon-to-be pensioners and students to co-create new solutions	20	Sharing own knowledge in social media
10	Introducing innovations to soon-to-be pen-sioners for their feedback	21	Providing peer-to-peer support when possible
11	Participating in idea exchange with voluntary sector		

acknowledged in previous research (cf. Bal et al., 2013; Pellicano et al., 2014; Rhodes et al., 2014).

6 Conclusion

In accordance with Agenda 2030 for SD and specifically SDG 11, world leaders are being encouraged to work together with enhanced commitment to advance the quality of life for the most vulnerable members of societies (Global Goals, 2021; United Nations, 2021a). Thus, SD is also about maintaining senior citizens’ active and healthy life and developing effective solutions for ageing at home that are related to the design of the living environment (Grazuleviciute-Vileniske et al., 2020) and age-friendly SLEs alike. As it is widely acknowledged in the literature, in order to achieve SDGs that make up Agenda 2030, it is crucial to support KM, which is the most critical means for promoting collaboration, improving access to knowledge, bringing together the inputs of the various stakeholders involved in SD activities (e.g., United Nations, 2016; Ulewicz & Blaskova, 2018; Mikalauskiene & Atkociuniene, 2019).

The results and discussion presented in this book chapter shed more light on how KM can be improved to support SD in building age-friendly SLEs to meet the needs of senior citizens. The research specifically focused on identifying conditions and practices that facilitate and encourage KC and KS between all QH regional stakeholders engaged in building age-friendly SLEs with the emphasis on the engagement and contribution of senior citizens as end-users. Drawing on the MCDA approach, the collaborative decision-making process engaging regional stakeholders that represented the Quadruple Helix of the Häme region, Finland, allowed for the development of the holistic analysis framework in the form of the collective cognitive map. Given the idiosyncratic characteristics and subjective elements of the proposed framework due to a specific research context and diverse decisions made by representatives of QH regional stakeholders with various kinds of expertise and experience, any generalisations cannot be formed without a careful analysis and reasoning. However, the constructivist and process-oriented approach of the applied methodology permits the continuous making of adjustments and updates based on new information and knowledge (Ferreira, 2016).

By incorporating the identified conditions and practices facilitating and encouraging KC and KS that are key determinants of KM, the proposed framework enables regional stakeholders to make analyses and decisions for improving KM. This well-structured framework and multiple factors explicitly considered in the decision-making process direct stakeholders to more accurate and better-informed decisions (Belton & Stewart, 2002). In terms of theoretical contribution, this research extends the body of the highly specialised and limited literature on KM in the context of SD, providing new insights into the conditions and practices for improving KM through KC and KS between QH regional stakeholders. Although the findings are idiosyncratic in nature, in theory they can provoke further interest and serve as an important starting point for future research on the impacts of effective KM on SD in building SLEs. From a methodological viewpoint, the research contributions are two-fold. First, the combined use of structuring methods and techniques (i.e., SODA, cognitive mapping, NGT and multi-voting) made the authors believe that it is a novel approach for a deeper exploration of the multidimensional concept of KM in the complex SD context. The second comes from the description of the applied process, which allows for replications in different contexts and/or with different groups of involved stakeholders, due to the process-oriented nature of the proposed framework (Bell & Morse, 2013).

The research findings indicated that having accumulated both professional expertise and personal experience, and with more time at their disposal, senior citizens showed genuine enthusiasm to be engaged in building age-friendly SLEs and the vast potential they have in developing collaboration and sharing knowledge and experiences with other stakeholders. The engagement of senior citizens as the end-users' group of QH regional stakeholders in the activities that contribute to KC and KS may lead to better decisions supporting SD in building age-friendly SLEs. Therefore, the role of the growing mass of senior citizens in developed countries as one of the end-user groups whose contributions can support SD requires further attention among researchers.

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A Piprecia-OCRA-G Decision-Making Approach to Selecting Sustainable Hotel Construction Projects

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Abstract Selecting the most appropriate type of hotel to build is an extremely important task that requires careful analysis and a methodical approach. This process is quite complex and demanding because, under the current business conditions, the selected hotel format must not only ensure profitable operations but also address key sustainability issues. This study's main aim was to develop and test a methodology based on multiple-criteria decision-making techniques that can facilitate the process of deciding which kind of hotel to construct. The proposed methodology was based on criteria that incorporated three primary sustainability dimensions—economic, ecological, and social aspects—and on the pivot pairwise relative criteria importance assessment method. The latter technique was used to determine the criteria's significance and the alternatives' grey operational competitiveness rating to enable the final ranking of these options. The proposed approach's applicability was confirmed by a case study of a real-life selection process of the most appropriate type of accommodation facility to build on the Republic of Serbia's Golija Mountain. The five alternative hotel construction projects were evaluated according to seven criteria. The results reveal that a townhouse format would be the most suitable for the Golija Mountain project from a sustainability perspective.

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1 Introduction

Hotel development projects often involve constructing accommodation facilities or creating hotel companies (Popovic et al., 2019b). Hotel property development is geared toward building the most appropriate facilities, which require significant time and financial resources. Because these projects are quite extensive, expensive, and time-consuming, they can be considered major investments. Constructing new accommodation facilities or specific types of hotels in the chosen destination is an extremely delicate issue because these decisions determine hotel businesses' future income and overall success. The facility format selected should fit the site's environment and offer comforts and services that will attract tourists.

Currently, decisions about which kind of hotel to build are influenced not only by economic factors but also sustainability aspects. Sustainability's role in hotel construction and operations has become a compelling issue that has received significant attention from researchers. For example, various studies have addressed the question of new construction technologies' impact on sustainable hotel design (Jabłońska et al., 2016). In addition, scholars have examined the issues raised by the green building strategy of energy efficiency when hotel buildings are retrofitted (Xu et al., 2011, 2015; Xu & Chan, 2013). Reid et al. (2017) explored sustainable practices in hotels operating in the Asia-Pacific region. The question still remains, however, of whether the hotel industry is completely ready to incorporate key sustainable development principles into their operations (Melissen et al., 2016).

The present context requires assessments of specific hotel construction projects that simultaneously consider sustainability's three main dimensions: economic, ecological, and social aspects. First, investors are interested in making a profit and receiving a return on the financial resources they expend on these projects. Second, practitioners are concerned about preserving natural and cultural environments. Last, the local population is interested in social benefits brought by particular hotels' construction and operations. All three aspects need to be taken into account in decision-making processes focusing on the most appropriate kind of hotel to construct, yet these influential factors are often mutually opposing.

Thus, the present study's application of multiple-criteria decision-making (MCDM) methods can be said to be completely suitable and justifiable. MCDM methods are a part of the field of operations research and management sciences, which seeks to facilitate decision-making processes dealing with a large number of conflicting evaluation criteria. Many different MCDM methods have been introduced in previous research, and comprehensive overviews have been conducted by Zavadskas and Turskis (2011), Zavadskas et al. (2014, 2015), Dammak et al. (2016), and Dhiman and Deb (2020).

Real-life problems are extremely difficult to express using precise figures because of the uncertainty and vagueness present in decision makers' environment. The current research, therefore, applied different extensions of previously introduced methods based on fuzzy, grey, or neutrosophic numbers. Various elements of the proposed approach have been presented in papers published by Mardani et al. (2015), Jayant et al. (2018), Liu and Gao (2018), and Seresht et al. (2018).

Different aspects of sustainable construction have been explored by researchers to determine the most suitable ways to achieve sustainability goals (Medineckiene et al., 2015; Ghorabaee et al., 2018; Zavadskas et al., 2018; Stojčić et al., 2019). Various existing studies have also focused on selecting the appropriate type of accommodation facilities to build. For example, Popovic et al. (2019a) applied the weighted sum method based on decision makers' preferred levels of performances. To incorporate the relevant environment's uncertainty and unpredictability, Karabasevic et al. (2019), in turn, used single-valued intuitionistic fuzzy numbers to guide choices of the best hotel format. Zolfani et al. (2018) assessed hotel construction projects with an evaluation model that incorporated environmental sustainability.

To achieve the present study's goal, the pivot pairwise relative criteria importance assessment (PIPRECIA) (Stanujkic et al., 2017a, b) and grey operational competitiveness rating (OCRA-G) methods (Stanujkic et al., 2017a, b) were used to determine the optimal type of accommodation facility for a specific hotel construction project. The PIPRECIA method was applied to ascertain the evaluation criteria's relative significance, while the OCRA-G method was utilized to rank options and make the final selection of the best alternative. The proposed methodology's applicability was confirmed with a real-life case: the identification of the most suitable hotel format for the Republic of Serbia's Golija Mountain construction project.

The Golija Mountain was declared a national park, which placed it under special protection, so the hotel type selected must fulfill the required sustainability criteria. Five alternative hotel projects were assessed using the seven evaluation criteria identified in a careful review of the literature. The input data relied on the *Master Plan for Tourism Development of Golija Mountain with a Business Plan* (Horwath HTL, 2007).

To showcase the proposed methodology's potential and research problem's optimal solution, the remainder of this paper is organized as follows. Section 2 explains the proposed methodology. Section 3 details the decision problem under study and provides a numerical example. The final section contains the conclusions drawn.

2 Methodology

The best hotel construction project that respects sustainability's main aspects was selected by applying the PIPRECIA and OCRA-G methods. The former method, as previously stated, was used to define the seven criteria's weights, while the OCRA-G method facilitated the final ranking of the hotel project options. A detailed explanation of the procedures followed in these two techniques is provided in the two subsections below.

2.1 PIPRECIA Method

Researchers have previously proposed using a broad range of MCDM techniques to determine criteria weights, such as the analytic hierarchy process (Saaty, 1977), analytic network process (Saaty, 1996), stepwise weight assessment ratio analysis (SWARA) (Keršuliene et al., 2010), and Kemeny median indicator ranks accordance (Krylovas et al., 2014). Each method has strengths, as well as specific flaws. Subsequent researchers have sought to improve on the existing approaches, proposing new techniques that can define criteria's significance more reliably. One such solution was introduced by Stanujkic et al. (2017a, b) as the PIPRECIA method.

The PIPRECIA technique has its roots in the SWARA method (Keršuliene et al., 2010), which has positives and negatives. The benefits of the latter method include being easy to apply so that even decision makers unfamiliar with the MCDM approach can quickly understand and apply the SWARA method to facilitate decision processes. However, this method is inconvenient to use in a group decision-making environment because SWARA requires decision makers to pre-sort the criteria under consideration. When a larger number of participants are involved in the process, obtaining the criteria's overall weight is quite complex. Finally, this method does not provide a way to check consistency, so decision makers cannot verify the results' reliability.

The PIPRECIA method eliminates the SWARA method's disadvantages while simultaneously preserving its strengths. The PIPRECIA method has previously been used to select mining methods (Popovic et al., 2019a), evaluate website quality (Stanujkic et al., 2018), rank cultural heritage sites (Popovic et al., 2019c), and choose e-learning courses (Jaukovic Jocic et al., 2020). This method's extensions have been applied to information technology (Stević et al., 2018; Tomašević et al., 2020), as well as finding optimal solutions for passenger rail operator businesses' balance sheets (Vesković et al., 2020).

The PIPRECIA method's computational procedure in a group decision-making environment can be presented as five steps:

- Step 1. Choose the participants who will be involved in the decision process.
- Step 2. Define the criteria that will be the basis of the evaluation process but without pre-sorting the criteria identified—unlike the SWARA method.
- Step 3. Every decision maker individually defines the relative significance of the criteria s_j^r, beginning with the second criterion, as shown in Eq. (1):

$$s_j^r = \begin{Bmatrix} >1 & when & C_j \succ C_{j-1} \\ 1 & when & C_j = C_{j-1} \\ <1 & when & C_j \prec C_{j-1} \end{Bmatrix} \tag{1}$$

– Step 4. The relative significance given by each individual participant is computed using Eqs. (2)–(4):

$$k_j^r = \begin{Bmatrix} 1 & j = 1 \\ 2 - s_j^r & j > 1 \end{Bmatrix} \tag{2}$$

$$q_j^r = \begin{Bmatrix} 1 & j = 1 \\ \frac{q^r_{j-1}}{k_j^r} & j > 1 \end{Bmatrix} \tag{3}$$

$$w_j^r = \frac{q_j^r}{\sum_{k=1}^{n} q_j^r} \tag{4}$$

in which k_j^r is the coefficient, q_j^r designates the recalculated weight, and w_j^r depicts criterion j's significance, determined in accordance with each decision maker r.

– Step 5. The criteria's overall relative significance is defined by Eqs. (5) and (6):

$$w_j^* = \left(\prod_{r=1}^{R} w_j^r \right)^{1/R} \tag{5}$$

$$w_j = \frac{w_j^*}{\sum_{j=1}^{n} w_j^*} \tag{6}$$

in which w_j^* represents the geometric mean of criterion j's significance, obtained by R participants.

2.2 OCRA-G Method

To facilitate the decision-making process's execution, previous researchers have proposed using various MCDM methods. In the present study, Stanujkic et al.'s (2017a, b) OCRA-G method was used to obtain the final ranking of the hotel project alternatives under consideration. This method is an improved version of the OCRA method originally introduced by Parkan (1994) and Parkan and Wu (1997). The basic OCRA method is capable of dealing with situations in which the criteria's relative significance depends on the alternatives in question, and, in some situations, the criteria are not applicable to all the options. This method enables a separate assessment of the alternatives in terms of cost and benefit criteria and combines the obtained aggregate ratings to determine the alternatives' overall competitiveness ratings. Thus, no important information is lost during the decision process.

Criteria usually cannot be precisely expressed through crisp numbers because decision-making environments are vague and unpredictable and decision makers normally deal with values with lower and upper boundaries. To resolve MCDM problems connected to uncertainties, Stanujkic et al. (2017a, b) proposed the OCRA-G method. The cited authors used this revised OCRA method to evaluate foreign-capital banks' efficiency (Özbek, 2015), select hotels (Işık & Adalı, 2016), and choose electronic devices (Ozdagoglu & Çirkin, 2019). The OCRA-G method has been discussed in various publications (Kosareva et al., 2018; Jahan & Zavadskas, 2019; Kaplinski et al., 2019; Ulutaş, 2019; Yao et al., 2019; Candan, 2020; Cheng et al., 2020). The latter method's procedure can be shown by the following steps, which rely on those presented in Stanujkic et al.'s (2017a, b) study.

2.2.1 Step One

Compute the aggregate grey performance ratings for the cost criteria using Eq. (7):

$$\otimes \bar{I}_i = \sum_{j \in \Omega_{\min}} w_j \frac{\max_j \otimes x_{ij} - \otimes x_{ij}}{\max_j \otimes x_{ij} - \min_j \otimes x_{ij}}, \tag{7}$$

in which $\otimes \bar{I}_i$ represents the aggregate grey performance rating of alternative i, which is obtained with the cost criteria. In addition, $\otimes x_{ij} \in \left[x'_{ij}, x''_{ij}\right]$ is the grey performance rating of alternative i with respect to criterion j, $\max_j \otimes x_{ij} \in \left[\max_j x'_{ij}, \max x''_{ij}\right]$, and $\min_j \otimes x_{ij} \in \left[\min_j x'_{ij}, \min x''_{ij}\right]$. Based on the operators of interval grey numbers, Eq. (7) can also be written as follows:

$$\otimes \bar{I}_i = \sum_{j \in \Omega_{\min}} w_j \frac{\left[\max_j x'_{ij}, \max_j x''_{ij}\right] - \left[x'_{ij}, x''_{ij}\right]}{\left[\max_j x'_{ij}, \max_j x''_{ij}\right] - \left[\min_j x'_{ij}, \min_j x''_{ij}\right]}, \tag{7.1}$$

or:

$$\otimes \overline{I}_i = \sum_{j \in \Omega_{\min}} w_j \frac{\left[\max {}_j x'_{ij} - x''_{ij},\ \max {}_j x''_{ij} - x'_{ij}\right]}{\left[\max {}_j x'_{ij} - \min {}_j x''_{ij},\ \max {}_j x''_{ij} - \min {}_j x'_{ij}\right]}. \tag{7.2}$$

2.2.2 Step Two

Calculate the grey linear performance rating for the cost criteria, as shown in Eq. (8):

$$\otimes \overline{\overline{I}} = \otimes \overline{I}_i - \min {}_i \otimes \overline{I}_i, \tag{8}$$

in which $\otimes \overline{\overline{I}}_i \in \left[\overline{\overline{I}}'_i, \overline{\overline{I}}''_i\right]$ stands for alternative i's grey linear performance rating obtained using the cost criteria and $\min {}_i \otimes \overline{I}_i \in \left[\min {}_i \overline{I}'_i,\ \min {}_i \overline{I}''_i\right]$. Eq. (8) can also be formulated as:

$$\otimes \overline{\overline{I}}_i \in \left[\overline{I}'_i - \min {}_i \overline{I}''_i, \overline{I}''_i - \min {}_i \overline{I}'_i\right]. \tag{8.1}$$

2.2.3 Step Three

Compute the grey aggregate performance ratings for the benefit criteria using Eq. (9):

$$\otimes \overline{O}_i = \sum_{j \in \Omega_{\max}} w_j \frac{\otimes x_{ij} - \min {}_j \otimes x_{ij}}{\max {}_j \otimes x_{ij} - \min {}_j \otimes x_{ij}}, \tag{9}$$

in which $\otimes \overline{O}_i \in \left[\overline{O}'_i, \overline{O}''_i\right]$ represents alternative i's grey aggregate performance rating. Eq. (9) can also be written as:

$$\otimes \overline{O}_i = \sum_{j \in \Omega_{\max}} w_j \frac{\left[x'_{ij}, x''_{ij}\right] - \left[\min {}_j x'_{ij},\ \min x''_{ij}\right]}{\left[\max {}_j x'_{ij},\ \max {}_j x''_{ij}\right] - \left[\min {}_j x'_{ij},\ \min {}_j x''_{ij}\right]} \tag{9.1}$$

or:

$$\otimes\overline{O}_i = \sum_{j\in\Omega_{\max}} w_j \frac{\left[x'_{ij} - \min{}_j x''_{ij}, x''_{ij} - \min{}_j x''_{ij}\right]}{\left[\max{}_j x'_{ij} - \min{}_j x''_{ij}, \max{}_j x''_{ij} - \min{}_j x'_{ij}\right]}. \tag{9.2}$$

2.2.4 Step Four

Calculate the linear performance ratings for the benefit criteria based on Eq. (10):

$$\otimes\overline{\overline{O}}_i = \otimes\overline{O}_i - \min{}_i \otimes \overline{O}_i, \tag{10}$$

in which $\otimes\overline{\overline{O}}_i \in \left[\overline{\overline{O}}'_i, \overline{\overline{O}}''_i\right]$ is alternative i's grey linear performance rating obtained with the benefit criteria and $\min{}_i \otimes \overline{O}_i \in \left[\min{}_i\overline{O}'_i, \min{}_i\overline{O}''_i\right]$. Eq. (10) can also be written as:

$$\otimes\overline{\overline{O}}_i \in \left[\overline{O}'_i - \min{}_i\overline{O}''_i, \overline{O}''_i - \min{}_i\overline{O}'_i\right]. \tag{10.1}$$

2.2.5 Step Five

Compute the overall grey performance ratings using Eq. (11):

$$\otimes P_i = \otimes\overline{\overline{I}}_i + \otimes\overline{\overline{O}}_i - \min\left(\otimes\overline{\overline{I}}_i + \otimes\overline{\overline{O}}_i\right). \tag{11}$$

Equation (11) can also be written as follows:

$$\otimes P_i \in \left[\overline{\overline{I}}'_i + \overline{\overline{O}}'_i - \min{}_i\left(\overline{\overline{I}}''_i + \overline{\overline{O}}''_i\right), \overline{\overline{I}}''_i + \overline{\overline{O}}''_i - \min{}_i\left(\overline{\overline{I}}'_i + \overline{\overline{O}}'_i\right)\right]. \tag{11.1}$$

2.2.6 Step Six

Choose the best alternative. Before the final ranking can be done, the overall grey performance ratings $\otimes P_i$ need to be converted into the overall crisp performance ratings P_i based on Eq. (12):

$$x_{(\lambda)} = (1-\lambda)\underline{x} + \lambda\overline{x} \tag{12}$$

in which λ represents the whitening coefficient and $\lambda \in [0, 1]$. When $\lambda = 0.5$, the whitened value is the interval grey number's mean, as shown in Eq. (13):

$$x_{(\lambda=0.5)} = \frac{1}{2}(\underline{x} + \overline{x}) \tag{13}$$

By varying coefficient λ, decision makers can examine different scenarios ranging from pessimistic to optimistic.

3 Case Study

This section describes the decision problem of which accommodation facilities to build on the Republic of Serbia's Golija Mountain. Given that this area is protected, the developers must select a type of hotel that will have mainly positive effects. The proposed methodology was applied using the project's real-life data to achieve two goals: (1) to test the proposed MCDM methodology's applicability and (2) to identify the optimal hotel construction project for the existing conditions. Section 3.1 details the problem in question, while Sect. 3.2 presents the numerical case study based on the real-life input data available.

3.1 Decision Problem

Golija Mountain is located in the southwest part of the Republic of Serbia. This mountain is rich in diverse flora and fauna, so the Serbian government has placed the Golija area under protection as the Golija National Park. The area has abundant natural and cultural resources that have not yet been properly transformed into tourism attractions. Tourism development will enhance the entire area's economic growth, but this undertaking requires decision makers to reconcile tourism projects' needs with the natural environment's preservation, as well as setting the boundaries for future development and growth.

The current situation and possibilities for tourism development on Golija Mountain thus need to be examined, and key projects that could be conducted need to be defined. To this end, Horwarth and Horwarth Consulting Zagreb was asked by Serbia's Ministry of Economy and Regional Development to prepare the *Master Plan for Tourism Development of Golija Mountain with a Business Plan* (Horwath HTL, 2007). This plan envisions the construction of specific accommodation facilities, along with other projects such as a wellness center and golf club.

As previously stated, the present study's aim was to assess the types of construction formats available to create tourist housing facilities that meet sustainability requirements. Five kinds of hotels listed as options for the Golija Mountain project were included in the evaluation. Their main characteristics are presented in Table 1.

Table 1 Types of accommodation facilities listed for construction

	Accommodation type	Description
A1	Destination hotel	A four-star full-service hotel dedicated to resting and relaxing, as well as organizing meetings and seminars
A2	Bed and breakfast pension	A three-star pension intended to house individual guests and families during both short and long stays
A3	Condo hotel	A three- or four-star hotel with condominiums intended for single users and families
A4	Townhouse	Three-star plus townhouses for private use that can accommodate several families
A5	Chalet	Three-star plus or four-star houses designed to accommodate single family groups and intended for private users with higher standards

Table 2 Evaluation criteria

Criteria		Measure	Optimization	Explanation
NU	Number of accommodation units per hectare parcel of land	Unit	Maximum	Number of rooms in hotel available for tourists to rent
SA	Surface area of accommodation units	Square meters	Maximum	Size of facility's accommodation units
IN	Investment	Euros/ square meters	Minimum	Amount of financial resources that need to be invested in the specific construction project
PA	Price of accommodation unit per overnight stay	Euros/ night	Maximum	Predicted price of overnight stay regarding a particular type of accommodation
EF	Ecological footprint	Gas per square meters/ day	Minimum	Aggregate index that measures the amount of natural resources needed to support of the target population's lifestyle, namely, ecological footprint estimated for overnight stays in each kind of accommodation
SW	Social wellbeing	Number of employees	Maximum	Number of jobs created when a specific accommodation facility opens
EP	Economic prosperity	Euros	Maximum	Projected profit per stabilized year

The presented alternatives were assessed using seven evaluation criteria. These criteria are, among other things, connected to sustainability's three main dimensions: ecological, economic, and social aspects. The criteria were selected based on Bamgbade et al. (2015) and Popovic et al.'s (2019a) work. The seven variables are presented in Table 2.

The main objective was to define the optimal type of accommodation facility to construct on Golija Mountain that will best fulfill the selected criteria. By addressing sustainability issues, the selected alternative will, through tourism, contribute to economic and social development, as well as to preserving nature.

3.2 Application of Proposed Methodology

The first step was to determine the relative significance of the selected criteria that would be the basis of further analyses. Three decision makers who are hotel industry experts were recruited to estimate the criteria's weight. To define these weights, the PIPRECIA method was applied. Figure 1 presents the criteria's relative significance according to each decision maker. Table 3 provides each criterion's overall weight.

As the above table shows, the most important criterion is economic prosperity (EP = 0.1656). The second place is occupied by price of accommodation unit per overnight stay (PA = 0.1570). Starting a hotel business inevitably influences the economic prosperity of the surrounding area, so this result is appropriate. In addition, the potential price of an overnight stay is a quite important variable that directly influences each accommodation facility's future financial success. According to the above results, the least significant criterion is surface area of accommodation units (SA = 0.1195). This smaller weight can be explained by how the accommodation units' quality and equipment are more important than their size.

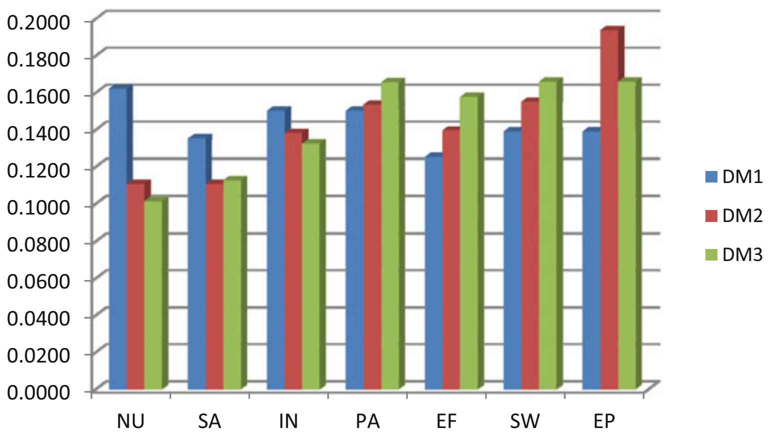

Fig. 1 Criteria significance by decision maker (DM)

Table 3 Criteria's relative weights

Criteria	Criteria's overall significance
NU	0.1226
SA	0.1195
IN	0.1407
PA	0.1570
EF	0.1408
SW	0.1537
EP	0.1656

Table 4 Initial grey decision matrix

	NU		SA		IN		PA		EF		SW		EP	
	Unit		Square meters		Euros/square meters		Euro/night		Gas per square meter/day		Number of employees		Euros	
	Maximum		Maximum		Minimum		Maximum		Minimum		Maximum		Maximum	
W	0.1226		0.1195		0.1407		0.1570		0.1408		0.1537		0.1646	
	x'	x''	x'	x''	x'	x''	x'	x''	x'	x''	x'	x''	x'	x''
A1	250	250	45	60	900	950	33	38	900	1250	155	170	2,100,000	2,400,000
A2	145	145	40	50	780	830	25	30	500	600	210	230	2,700,000	2,900,000
A3	490	490	45	60	850	900	23	28	800	900	40	60	850,000	880,000
A4	365	365	75	95	880	930	25	30	700	760	80	140	3,500,000	3,800,000
A5	220	220	90	120	900	1000	42	47	690	740	50	70	3,900,000	4,300,000

Note: W = weight

Table 5 Application of OCRA-G method

Alternatives	$\otimes\bar{I}_i$		$\otimes\bar{\bar{I}}_i$		$\otimes\bar{O}_i$		$\otimes\bar{\bar{O}}_i$		$\otimes P_i$	
	x'	x''	x'	x''	x'	x''	x'	x''	x'	x''
A1	−0.09	0.12	−0.21	0.21	0.58	1.05	0.11	0.86	−0.62	1.45
A2	0.08	0.25	−0.03	0.34	0.69	1.21	0.22	1.01	−0.33	1.74
A3	0.00	0.15	−0.12	0.24	0.19	0.47	−0.27	0.27	−0.91	0.91
A4	0.03	0.18	−0.09	0.27	0.77	1.36	0.30	1.16	−0.30	1.82
A5	0.02	0.18	−0.10	0.27	0.78	1.25	0.31	1.06	−0.30	1.72

Table 6 Ranking of five alternatives

Alternatives	P_i	Rank
A1	0.42	4
A2	0.70	3
A3	0.00	5
A4	0.76	1
A5	0.71	2

Table 7 Ranking results obtained based on different values of γ

	$\gamma = 0$		$\gamma = 0.5$		$\gamma = 1$	
	P_i	Rank	P_i	Rank	P_i	Rank
A1	−0.62	4	0.42	4	1.45	4
A1	−0.33	3	0.70	3	1.74	2
A3	−0.91	5	0.00	5	0.91	5
A4	−0.30	1	0.76	1	1.82	1
A5	−0.30	2	0.71	2	1.72	3

Table 4 lists the grey input data for the five alternative accommodation facilities regarding the evaluation criteria identified. Each criterion's significance is also shown.

The data presented in the above table are based on statistics provided in *Master Plan for Tourism Development of Golija Mountain with a Business Plan* (Horwath HTL, 2007). The different types of accommodation facilities' ecological footprint was estimated based on Castellani and Sala's (2008) research. The grey aggregate and grey linear performance ratings for the cost and benefit criteria were calculated using Eqs. (7)–(10) (see Sects. 2.2.1–2.2.4), while the final grey performance ratings were obtained by applying Eq. (11) (see Sect. 2.2.5). The results are shown in Table 5. The final rankings for $\lambda = 0.5$ are presented in Table 6.

When $\lambda = 0.5$, the townhouse alternative (i.e., A4) stands out as the best option. Because the analyses included testing for potential changes in the alternatives' rankings, the coefficient λ is variable. The results are shown in Table 7. Figure 2 presents the five options' relative positions in different scenarios that range from pessimistic to optimistic.

In all three scenarios, the alternative ranked first does not change, which indicates that the townhouse alternative (i.e., A4) is an optimal choice under the given conditions. The ranking also does not change in terms of the last position as the

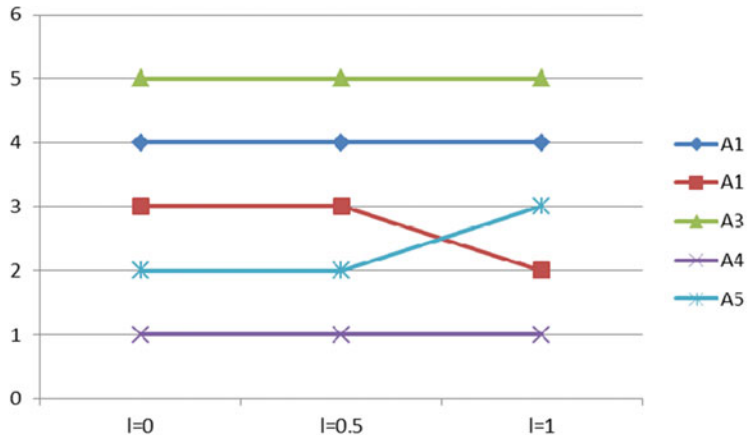

Fig. 2 Ranking of alternatives in relation to different values of γ

condo hotel option (i.e., A3) is ranked the lowest in all three scenarios. Keeping Table 4 above in mind, the conclusion can be drawn that the highest ranking alternative is a compromise solution. Townhouses fulfill all the requirements laid out in the seven criteria, especially those connected to sustainability issues. Although this alternative was not assigned the highest values for all requirements, it complies with the criteria that the experts considered the most important. A satisfactory number of jobs created, relatively low predicted ecological footprint, and high predicted profit per stabilized year thus justify this alternative's top position.

4 Conclusion

The hotel industry cannot develop in isolation from contemporary trends, so sustainable development issues are also important in this sector. Currently, hotel managers must pay attention not only to hotel operations' economic aspects but also to ways these facilities will contribute to the local population's social wellbeing and affect the environment. These questions are connected both to hotels' ability to function well and to issues that arise at the moment when the most appropriate type of hotel is selected for each construction project. At this point, a number of different criteria need to be considered, which additionally complicate this task because these variables often pull in opposite directions. The selection of the optimal solution for each case thus requires a methodological approach and in-depth analyses.

The present study applied a sustainable MCDM approach to facilitate the assessment and selection of the best type of accommodation facility for a proposed construction project. The proposed approach is based on the PIPRECIA and OCRA-G methods. The former method is used to determine criteria weights. The main reasons for including this method in the procedure are its simplicity and ease of use in group decision-making processes. In this research, the PIPRECIA technique produced appropriate, satisfactory results and contributed to facilitating the selection process.

OCRA-G method, in turn, was used to conduct the final assessment and ranking of the alternatives in question. This method was applied because the input data connected to real-world problems rarely can be expressed in crisp numbers. These data's uncertainty and vagueness also means that values can vary from lower to higher figures. The OCRA-G method enables decision makers to manage input data that does not include exact values. In addition, the computational procedure involved is relatively simple and produces acceptable results.

The proposed approach's usefulness was demonstrated based on the real-life case of the planned development of hotel facilities on the Republic of Serbia's Golija Mountain. To address the planned construction's sustainability dimensions, a set of seven criteria were defined with reference to Bamgbade et al. (2015) and Popovic et al.'s (2019a) studies. The present results indicate that the townhouse alternative is the best choice according to the selected criteria.

When these findings are compared with those reported by Popovic et al. (2019a), the current study's first-place option was ranked fourth, which also occurred in Karabasevic et al.'s (2019) research. However, the criteria selected for the cited studies' evaluation procedure did not include variables connected to sustainability dimensions. In the present research, the specific location where the accommodation facilities would be built meant that sustainability dimensions had to be considered. The townhouse option was ranked first because this format does not leave a serious ecological footprint, social benefits expressed as the number of jobs created are quite good, and the predicted profit is high. The remaining characteristics are also extremely satisfactory, which ultimately contributed to this alternative's positive evaluation.

This study was subject to specific limitations that were, first, connected to the criteria selected. The results could have been more representative and reliable if the sustainability dimensions had been represented by a larger number of criteria. Second, the determination of the criteria's weight was based on only three experts on the hotel industry, so, although the variables' overall significance was calculated based on geometric means, the results were quite subjective. This limitation could have been minimized by recruiting a larger number of decision makers and applying an appropriate method for more objectively defining the criteria's weight. Last, more interesting results could have been obtained if a combination of objective and subjective methods had been utilized.

Nonetheless, the proposed approach involving the PIPRECIA and OCRA-G methods provided acceptable results and facilitated the selection of an alternative that satisfactorily applies sustainability principles. The computational procedure was quite easy to apply, which helped simplify the decision-making processes. The proposed methodology's application should not be limited to selecting appropriately sustainable forms of accommodation facilities, and its possibilities and potential also need to be tested in other areas of work and business.

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A Decision Making Model for Order Release in an Assembly Job-Shop to Improve Business Performance and Sustainability

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Abstract The assembly job-shop scheduling problem concerns the parts processed in a job shop manufacturing system followed by their subsequent assembly operations. The order release mechanisms impact both on the production performance and the buffer levels that is relevant for enterprise's sustainability. This chapter proposes a decision-making model to release the orders in the shop-floor with the aim of improving customer satisfaction and production system performance. The suggested model detects the parts needed by customer's orders to forecast the parts necessary for the assembly operations and keep a stable workload of the job-shop. The chapter shows the results of a simulation environment that has been developed to evaluate the model, and the obtained performance results. The simulation results corroborate the usefulness of the model to deal with the assembly job-shop scheduling problem and performance improvement.

Keywords Assembly job shop · Workload control · Order release · Discrete simulation environment · Decision making model

1 Introduction

An assembly job shop problem deals with the processing of N parts or components in a job-shop manufacturing system. Different typology and number of parts can compose each customer's order and their assembly can start only when all parts are provided by the job-shop manufacturing.

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This entails a scheduling problem more complex than the classical job-shop scheduling problem.

Moreover, the methodology used in the case of general job-shop has significant computational complexity and excessive computational time. Therefore, the assembly job shop problem can be more properly handled by heuristic methodologies.

The use of a heuristic approach is corroborated by the possibility of employing an order release control policy to send to the shop floor the production orders of components. The production orders are kept in a pre-shop pool before release (Ragatz & Mabert, 1988). The main reasons to keep customer's orders in the pre-shop pool are: (1) avoiding to release customer orders with due date away from the present date; (2) reducing the work in process in the manufacturing system and the inventory holding costs for finished goods; (3) limiting the work in process inventory to a desired level.

In addition, the buffer levels that contribute to the entire work in process, affect energy consumption and, in turn, the systems' sustainability in terms of costs and environmental impact.

Among the different approaches to job shop, many studies have demonstrated the effectiveness of the WorkLoad Control (WLC) approach (Oosterman et al., 2000; Thürer et al., 2010). Referring to assembly job-shop, the exploitation of the WLC is more recent (Stevenson et al., 2011; Thürer et al., 2011, 2012).

This chapter addresses the decision problem regarding the order release control in an assembly job-shop environment.

In particular, it is proposed a decision making approach based on controller's activities, that checks the components' demand in the light of the product orders, and on the use of the WLC control policy to release the components in the manufacturing system stage. A simulation environment is developed to test the proposed approach.

Drawing on the past observations (i.e. average and deviation of components and orders data), the controller forecasts the components required to accomplish the customer's orders. Then, the forecast of the components is compared with the buffers' level of each component in the assembly stage.

If the WLC control policy is verified the controller releases the orders of the components.

The proposed approach aims to drive decision making for order release in the assembly job-shop in order to gain the following performances: (1) improved customer satisfaction, (2) more uniform manufacturing utilization; (3) keeping a constant speed in consuming each part in the assembly stage.

The simulation environment is built by using EXTENDSIM®.

In order to test the proposed approach, three benchmarks simulation models are developed: (1) one model without any policy, (2) one model with EDD (Earliest Due Date) management of the queues and (3) one model with a fixed target level of the buffer of each component in the assembly stage.

The chapter is organized as follows. Section 2 presents the research background. The reference context is explained in Sect. 3. Section 4 describes the proposed approach. The simulation environment is presented in Sect. 5, while Sect. 6 provides a discussion of the simulation results. Finally, conclusions and future research paths are drawn in Sect. 7.

2 Research Background

The development of approaches to solve the scheduling problem in assembly job-shops has attracted the attention of many scholars. Recently Framinan et al. (2018) and Komaki et al. (2019) have surveyed the assembly scheduling problems and described their trends.

Many of these researches focused on the sequencing rules (dispatching) and order review/release mechanisms, fairly simplifying the assembly job-shop context.

Bertrand and Wakker (2002) investigated the order release and flow time allowance policies on the assembly orders flow time and assembly order due date performance. The research results show that the best performance is obtained with simultaneous work order release, an average operation flow time allowance equal to the average operation waiting time and equalized flow time allowances per work order in an assembly order.

Thiagarajan and Rajendran (2003) carried out an extensive study comparing the efficiency of 10 sequencing rules against 11 cost-based performance measures in a stochastic assembly job shop that produced three classes of BOM (Bill Of Material, single, two-level and three-level structures). The main result of the study was that variations of TWKR (Total WorK content Remaining) designed to incorporate cost factors performed very well with respect to almost all performance measures. An extension of that work is presented in Thiagarajan and Rajendran (2005) with similar results.

Yokoyama (2004) addressed the scheduling problem for two-stage production system including machine operations, setup operations and assembly operations. The objective function is the mean completion time for all products. A solution procedure using pseudo-dynamic programming is proposed to obtain a near-optimal schedule. A tight lower bound is developed to evaluate the accuracy of the near-optimal schedule. Computational experiments are provided to evaluate the performance of the solution procedure. It has been found that a good near-optimal schedule is obtained efficiently by the proposed solution procedure.

Pathumnakul and Egbelu (2006) addressed the problem of minimizing the weighted earliness penalty in assembly job shops. Because of the computational time intensity associated with the problem, a heuristic was developed to solve the problem. The heuristic decomposes the problem into several single machine problems. Solutions to the single machine problems were used to construct the solution to the original problem. The effectiveness of the heuristic was evaluated by solving a set of test problems. The results of the test problems demonstrated that the heuristic is effective in solving the problem.

Also, Natarajan et al. (2007) conduct an extensive study investigating the efficiency of a set of 12 sequencing rules in an assembly job shop that produced three configurations of BOM (single, two-level and three-level structures). Eight rules of the set were proposed. Six performance measures were selected as optimisation criteria. Results indicated that four of the proposed rules based on different variations of the ODD (Operation Due Date) rule performed well, on the whole, with respect to both performance criteria.

Chan et al. (2008) proposed a genetic algorithm approach and simple dispatching rules to solve the scheduling problem in assembly job-shops.

Wong et al. (2009) proposed a model to minimize the total lateness cost of all final products by the application of lot streaming technique extended to a resource–constrained assembly job shop scheduling problem. An innovative approach with a Genetic Algorithm (GA) is proposed. The goodness of the model is tested by the Particle Swarm Optimization (PSO), benchmark method. Computational results suggest that GA can outperform PSO in terms of optimization power and computational effort for all test problems.

Omkumar and Shahabudeen (2009) proposed a new optimization heuristic based on an ant colony algorithm in assembly job shops. The performance measures of the proposed approach are compared with the dispatching rules.

Lu et al. (2011) deal with an assembly job-shop scheduling problem considering two phases of control: order review/release (ORR) and dispatching rules. The aim of the research is to evaluate the ability of different combinations of ORR-dispatching rules in optimising due date and flow time related performance measures. The main limit of the study concerns the assumption that the assembly operation is assumed to be completed instantly with a negligible operation time. This not allows evaluating the work in process of the components in the buffers before the assembly. Moreover, the performance measures studied are limited.

Baykasoğlu and Göçken (2011) developed simulation models which allow exploring the effect of each decision level within a workload control concept. The results reveal that simultaneous consideration of decision levels is critical and can improve the effectiveness of production planning and control.

Pereira and Santoro (2011) proposed a heuristic method for simulating the operations scheduling process in assembly job shop system based on the use of sequencing rules to drive the process. The sequencing rules tested were chosen to be variations of 'classical' rules redesigned to use explicitly or implicitly the estimated waiting time and preliminary operation due date.

Thürer et al. (2012) extended the applicability of WLC to assembly job shops by determining the best combination of: (1) WLC due date setting policy, (2) release method and (3) policy for coordinating the progress of work orders. Results indicate that WLC can improve performance in assembly job shops and outperform alternative control policies.

Renna (2012) proposed an order acceptance decision as an interface between the customer relationship management and the production planning activities of the manufacturing system. The proposed policy is integrated with production planning activity; the policy is used to decide acceptance/rejection, by using the information provided by the production-planning model. The simulation results show the robustness of the proposed approach and provide the information to set the threshold value of the suggested approach.

Wong and Ngan (2013) proposed two hybrid evolutionary algorithms, hybrid genetic algorithm (HGA) and hybrid particle swarm optimization (HPSO) to minimize the makespan in assembly job-shop scheduling problem environment with lot streaming (LS) technique. The scholars launch an experiment to compare the performance of HGA and HPSO in minimizing the system makespan under different operating conditions. Computational results suggested that HGA is significantly better than HPSO under various operating conditions with and without LS.

A limitation of the proposed model is that it is not directly applicable to situations in which the lot size is not discrete or the size is fixed in terms of length, weight, etc. For example, in the production of printed circuit board (PCB), a lot is usually a roll of thin copper sheets measured in weights.

Renna (2015, 2020) investigated the workload control in manufacturing systems under continuous order release by a simulation environment. The main issues investigated by the scholar regard the selection of the order to release, among the orders in a pre-shop queue, the workload computation based on the routing of the orders and the workload norm.

Genetic algorithms have been proposed by Jung et al. (2017) to solve two-stage assembly flow shop scheduling problem to assemble products having dynamic component-sizes.

The analysis of the recent studies on the scheduling problem in assembly job-shops highlights the presence of some limitations that can be summarized as follows:

(a) the major part of the research concerns heuristic approaches (genetic algorithm, ant colony, etc.); these approaches lead to a greater computational workload when the assembly job shop context is characterized by a huge number of machines;
(b) often the analyzed context is characterized by relevant simplification as the assembly stage is characterized by instantaneous activity;
(c) the approaches proposed in the literature are tested in manufacturing systems where the exceptions and rapidity of alterations were not investigated. Most tests are conducted in static conditions. Moreover, the performance measures investigated are often limited.

This study attempts to overcome the above limits as follows:

(a) it is a proposed WorkLoad Control policy based on the workload of the manufacturing system stage and the possibility to release the orders of the components in advance, with the aim of improving the customer performance;
(b) several performance measures are evaluated, considering a realistic test case with minor limits. In particular, the evaluated performance regard customer's orders, the manufacturing system and the buffer levels of the assembly stage;

(c) a simulation environment is used to test the proposed approaches when customer demand is characterized by changes. This allows evaluating the proposed approach in dynamic conditions.

3 Reference Context

The reference context draws from previous classical assembly job shop problem studied in Ragatz and Mabert (1988) and Ahmed and Fisher (1992). However, this study proposes an assembly job shop that overcomes several simplifications characterizing its classical treatment, with the aim of obtaining a more realistic view of the manufacturing system context.

Figure 1 shows the configuration of the assembly job shop considered. The customer demand is characterized by the products order requested. The order release process controls the workload of the shop-floor and decides if the product order can be released in the shop floor; otherwise, the product order waits. The product orders that wait are managed by Earliest Due Date (EDD) rule. When the product order is released, the orders of the components that compose the product orders are released in the shop floor requiring the raw material. In this research, it is considered that the raw material is always available. The shop floor consists of six machines that are able to perform all the manufacturing operations required by the components. For each manufacturing operation, the components are assigned to the machines following a workload policy. The manufacturing machines of the shop floor are able to manufacture all the operations required by the components. However, each machine can process one operation at a time and no preemption of operations can be allowed. This means that two consecutive operations are performed with disjoint visits to the machines. The finished components are provided to the buffers of the assembly station to assemble the final product. The assembly stage works in a Make To Order policy; therefore, only when a customer order waits for the final product the relative order is released in the assembly station to satisfy the customer order.

In the chapter the following notations are assumed:

k denotes the finished assembled product ordered;

j denotes the component typology.

i denotes the manufacturing operations for the components

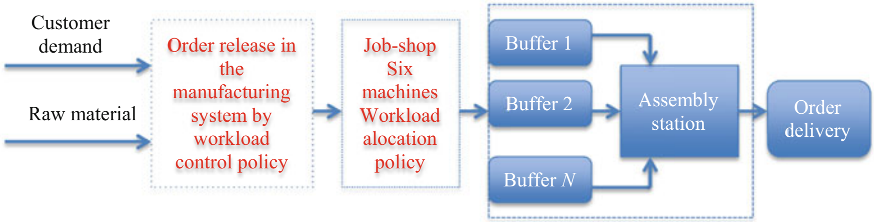

Fig. 1 Assembly job-shop configuration

$$X_j^k = \begin{cases} 1, \textit{if the component typology i needs to be assemble in the product order k} \\ 0, \textit{otherwise} \end{cases}$$

$Q^k{}_j$ denotes the quantity of components of typology *j* to assemble for the order *k*.

$N^k{}_j$ denotes the number of manufacturing operations for the product typology j and the order k.

$p^k{}_{ij}$ denotes the processing time of operation *i* for the component *j* of order *k*.

dd_k due date of the order *k*.

pa_k denotes the assembly time of the order *k*.

The benchmark used for the proposed approach works as follows (*benchmark*). The customer orders are instantly released in the manufacturing systems without any workload control policy.

4 Proposed Approaches

Two approaches are proposed to perform the control release of the work orders in the pre-shop pool. In particular, it is assumed that all orders are accepted and the raw materials for the components are always available. When the customer inputs a product order, all corresponding work orders enter in the pre-shop pool to await release. The suggested approaches are based on the work control of the shop-floor. A work order that waits in the pre-shop pool can be released in the shop floor if the Work In Process (*WIP*) of the shop floor is lower than a fixed threshold (Thr_{wip}) as shown in expression (1):

$$WIP \leq Thr_{wip} \tag{1}$$

The approaches concern the release of work orders that are not related to product orders in the shop-floor when the work in process of the shop floor is at low level. This allows to uniform the workload of the machines and improves the response rapidity to the customer orders. The drawback is the higher level of the buffers' level in which the components wait for the assembly process. In the following the approaches are described more in detail.

Approach 1(thrb)

This approach is used as a second benchmark for the proposed original approach. It is fixed a target value for each buffer of the components in the assembly stage ($thrb_j$). Then, a "*controller*" computes the difference between the target value and actual buffer level for each component as shown in expression (2).

$$\max\left\{ \max_j \left(Thrb_j - buffer_j \right); 0 \right\} \tag{2}$$

If the work in process is lower than the fixed threshold (Eq. 1), the controller releases the work order of the component *i* that verifies the expression (2); If the expression (2) is greater than 0, otherwise no work order is released. The work order released by the controller has a lower priority of the "*normal*" work order released in the queue of machines.

This is a simplified approach that inputs the components in the manufacturing system when the workload is low. This leads to keep a uniform utilization of the manufacturing system during the production horizon and try to reduce the wait time of the customers because the components are produced in advance.

Approach 2

This approach is characterized by a parameter to fix: $Thrb_i$. This parameter needs to be adapted when the conditions change such as customer demand behavior, the mix of the components required, manufacturing system configurations, etc. In order to avoid the definition of this parameter, it is proposed the following method.

In order to avoid the above limits, the controller observes the average and standard deviation (*variance*) of the components required for the customer orders. The average and standard deviation are combined to forecast the components required by the customer orders by the expression (3).

$$index_j = average_j + K * variance_j \quad (3)$$

The parameter *K* can be used to evaluate the probability to forecast the real demand of the components. In particular, it is supposed a normal distribution of the components (not of the product orders). In this case, the parameter K characterizes the probability of the normal distribution as shown in Fig. 2. A greater value of K allows increasing the probability that the variable (components' demand) is captured by the forecast.

For example, Table 1 reports the percentage of the area under the normal curve considering the average value ±the standard deviation.

The mean of the parameter K is the following. If the value of *K* is higher than the buffer level of the components is higher and the customer service level is higher (lower time to satisfy the orders). The weakness is the higher buffer levels that leads to higher costs related to work in process of components. Therefore, the parameter *K* can be evaluated in order to take into account the tradeoff between the customer service level and the costs of work in process.

Then, it is evaluated the expression (4) for choosing the component type order to release in the manufacturing system.

$$\max\left\{\max_j\left(index_j - buffer_j\right); 0\right\} \quad (4)$$

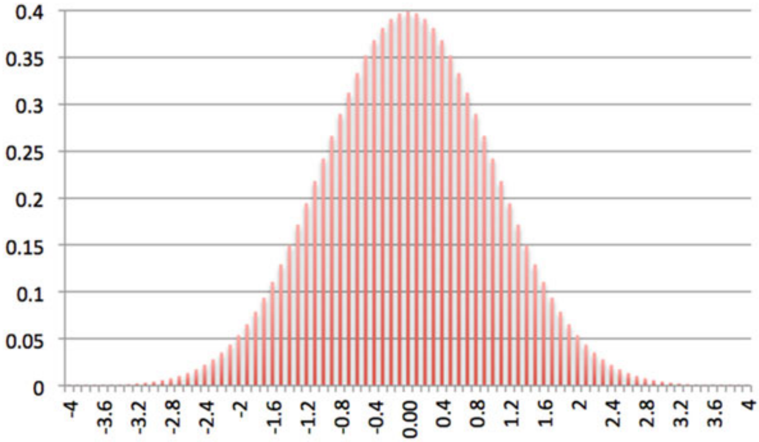

Fig. 2 Normal distribution–probability distribution function

Table 1 K value

K	Area under the normal curve (%)
1	68.27
1.5	86.64
2	95.45
3	99.73
4	99.99

The controller releases the work order of the component i that verifies the expression (4); If the expression (4) is greater than 0, otherwise no work order is released. The work order released by the controller has a lower priority of the "*normal*" work order released in the queue of machines.

Figure 3 shows how the proposed approach works and interacts with the assembly job shop.

5 Simulation Environment

The simulation environment is based on the multi-domain software ExtendSim® by Imagine That Inc. ExtendSim is a simulation program for modeling discrete event, continuous, agent-based, and discrete rate processes. There are four ExtendSim packages: CP for continuous processes; OR (operations research) which adds discrete event; AT (advanced technology) which adds discrete rate, a number of

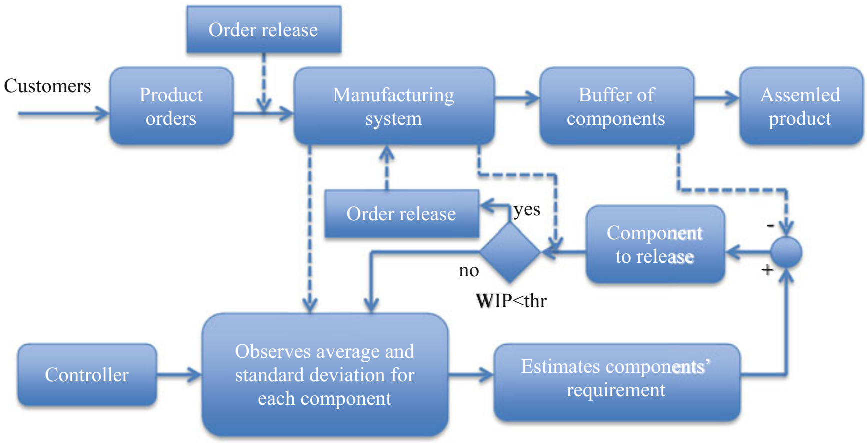

Fig. 3 Activities of the proposed approach

advanced modeling features, Stat Fit for statistical distribution fitting; and Suite which adds 3D animation.

The combination of agent-based, information and OR allows to develop a complete simulation environment that is able to connect to simple industrial information as access and excel used in small and medium enterprises.

These features make ExtendSim particularly suitable for this research work. The simulation environment settings and the scenarios analyzed are described in the following.

The product orders arrival follows an exponential distribution with mean equal to 4. This value leads to manufacturing utilization of about 80% for the benchmark model.

Each product order k is composed by a number of component typology j $Q^k{}_j$ to assemble extracted from a uniform distribution UNIF [2,6]. The number of manufacturing operations N_{op} for each component is extracted from a uniform distribution UNIF[1,6]. The processing time of each operation i $p^k{}_{ij}$ follows an exponential distribution with a mean value of one. The assembly operation time follows an exponential distribution with a mean value of one (Lu et al., 2011). The due date of a product is set using the TWKCP (total work content on the critical path) rule (Hatchuel et al., 1997).

$$DD_k = T_k + M \times N_{op} \tag{5}$$

where T_i is the time in which the customer inputs the order. The components that compose the customer order have the same due date. The multiplier M is extracted by a uniform distribution UNIF [3,5].

The above simulation environment is used to the test the proposed approaches.

Table 2 demand fluctuation

Time	Expo parameter
0	4
200	6
400	2
600	5
800	4

Table 3 Demand of components for the product orders

Component	Demand
1	UNIF[1–5]
2	UNIF[1–3]
3	UNIF[4–6]
4	UNIF[8–10]
5	UNIF[1–10]
6	UNIF[7–10]

The performance measures of the approaches, i.e. approach 1 and approach 2, are compared to two benchmark models without order release control. Therefore, the models simulated are the following:

– *bench1*: it is considered a model without order release control policy and FIFO queue management;
– *bench2*: it is considered a model without order release control policy and EDD queue management;
– *approach1 (thrb)*; the value of the threshold Thb_i is fixed to six components for each buffer (see expression 2), because the maximum number of components required by a product orders is 6.
– *approach2*; the approach is performed for three values of the parameter K: 1,1.5 and 3.

The experimental classes tested are the following:

– case 1: the experimental conditions are described the following: product orders arrival with exponential distribution and mean equal to 4, number of component typology with uniform distribution UNIF[2,6], number of manufacturing operations with uniform distribution UNIF[1,6], processing and assembly operation time with exponential distribution and a mean value of one, due date of a product set using the TWKCP rule;
– case 2: some demand fluctuations are considered. The mean value of the exponential distribution changes as shown in Table 2. The demand fluctuation is characterized by the change of the exponential every 200 unit time.
– case 3: the product orders consist of different distribution for each component typology as shown in Table 3.
– case 4: it is the combination of cases 2 and 3.

For each experiment class, a number of replications able to assure a 5% confidence interval and 95% of confidence level for each performance measure have been conducted.

The performance measures evaluated to compare the models are the following:

- average delay of the product orders (delay);
- average number of product orders that wait in queue (queue ord.);
- average throughput time of the product orders (thr. time);
- average work in process of the shop floor (WIP);
- average utilization of the machines (utilization);
- average level of the components in the assembly buffer station (av buffer);
- standard deviation level of the components in the assembly buffer station (dev buffer);
- number of product orders completed over the simulation horizon (completed).

6 Numerical Results

Several simulations have been conducted in order to obtain the best value for the workload control setting the maximum value of WIP.

Figure 4 reports the benefits of the Earliest Due Date policy for the average delay of the product orders performance (benchmark 1 used as a base for the percentage computation).

As the reader can notice, the greater benefit is obtained for case 1 (stable demand) and case 2 (stable demand and different components distribution for the product orders). The benefit is lower when the fluctuations characterize the customer demand (case 2 and 3).

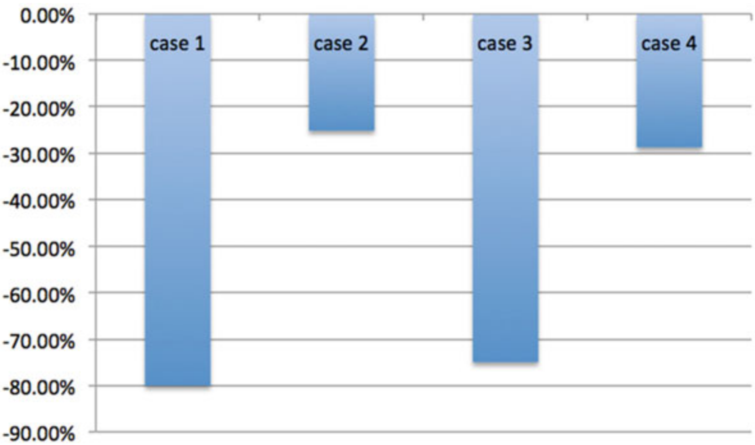

Fig. 4 Earliest due date: delay performance

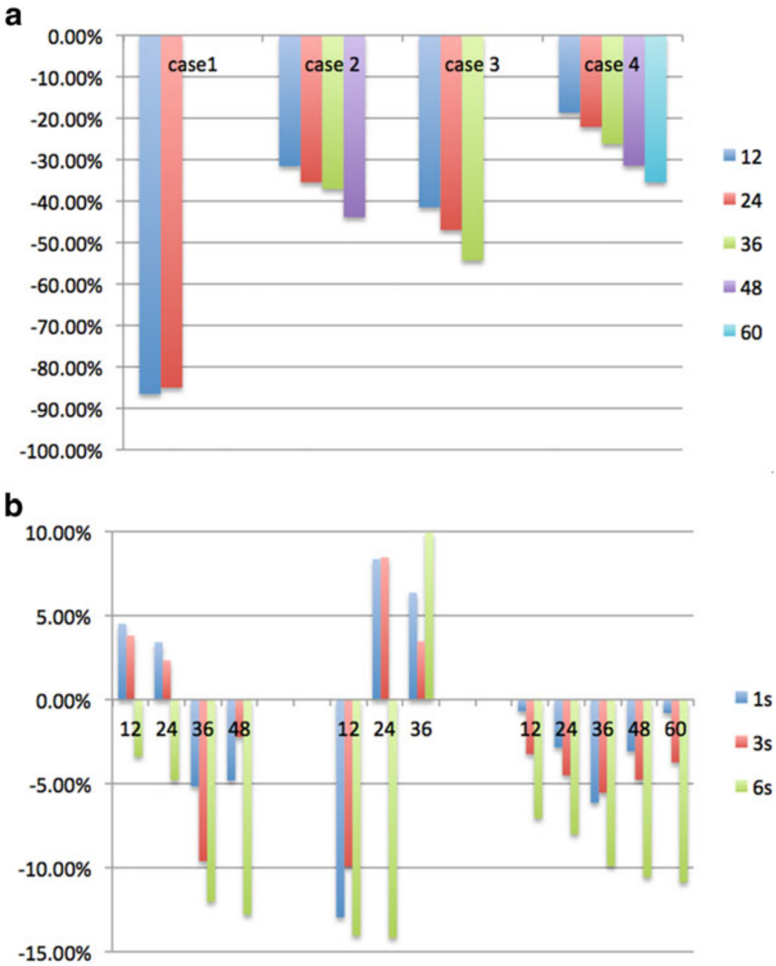

Fig. 5 (**a**) Delay comparison *approach 1* vs. EDD. (**b**) Delay comparison *approach 2* vs. *approach 1*

Figure 5a shows the comparison of the *Thrb* with benchmark 2 (EDD) considering the maximum value of the WIP (from 12 to 60 as shown in Fig. 3).

The *Thrb* approach (approach 1) allows to improve significantly the delay performance for all cases tested; in case of fluctuations of customer demand, it is necessary to increase the maximum value of WIP to improve this performance. In particular, case 4 (demand fluctuations and components with different distributions) is characterized by the higher value of WIP (equal to 60) to reach better performance. Therefore, the proposed approach is a promising control policy to improve the delay performance.

Figure 5b shows the comparison of the delay performance between *approach 2* and *approach 1* for different values of K (1 s, 2 s and 3 s). This comparison

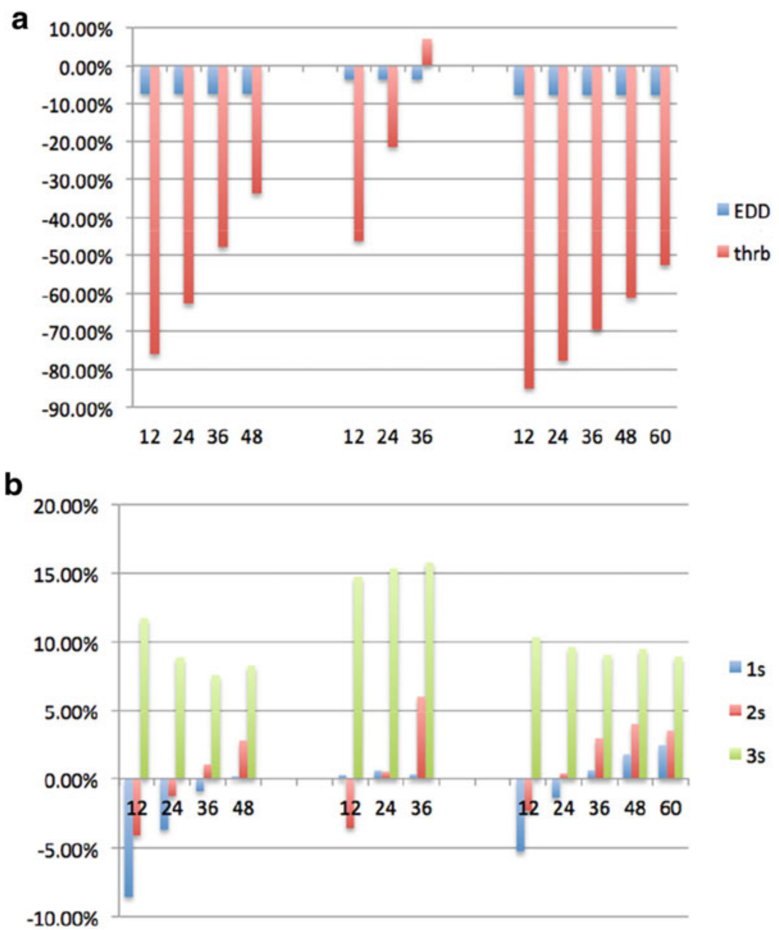

Fig. 6 (**a**) WIP comparison approach 1 and EDD vs. Benchmark 1. (**b**) WIP comparison approach 2 vs. approach 1

highlights how the adaption of the threshold level of the buffers can improve the delay performance.

The proposed approach 2 works better when the demand is characterized by fluctuations and the components have different distributions (case 4); the increase of the parameter *K* allows to improve the benefit compared to approach 1 (static threshold level). In case of different distribution of the components, and stable demand (case 3), the approach 2 leads to better results in some cases: 12 and 24 WIP values for the workload control policy and *K* equal to 3.

Figure 6a analyses the total Work In Process (WIP of the manufacturing system and the components that wait in the buffers).

The EDD policy reduces the total WIP (less than 10%), but the approach 1 reduces drastically the total WIP. This is obtained by the workload control policy that reduces the WIP of the manufacturing systems increasing the components in the buffers.

The simulation results are reported in terms of percentage difference compared to the *bench1* case.

Figure 6b shows the WIP performance of *approach 2* compared to *approach 1*.

The best performance of the approach 2 in terms of average order delay is paid by the increasing of the components in the buffers that increase the total WIP. The parameter *K* allows the control of the trade-off between the performance of delay and the increasing of total WIP.

In a pulling system (assembly stage) the consuming speed of the components needs to be more uniform, in this way the workload of the manufacturing system is distributed among all components. This leads to realize a smoothed production (Monden, 1983). This performance is evaluated considering the deviation of the buffers' level.

Figure 7a shows the deviation standard of the buffers 'level between the EDD and the approach 1 compared to the benchmark.

The EDD allows to uniform the level of the buffers of the components, while the approach 1 is characterized by a very high difference between the buffers' level of the components.

Figure 7b shows the deviation standard of the buffers' level between the *approach 2* and the approach 1 (*thrb*).

Approach 2 allows to obtain a more uniform distribution of the components among the different buffers before the assembly station improving the consumption of the components and the allocation of the space in the assembly stage.

Figure 8 shows the manufacturing utilization of the approach 2, EDD compared to the benchmark1. Approach 2 has the same utilization of approach 1.

The proposed approach 1 and 2 increase the manufacturing utilization, because when the demand is low the components for the foreseen customer demand are produced. This allows to keep a more uniform utilization of the manufacturing system during the planning horizon.

Table 4 reports the standard deviation of the manufacturing utilization for the case 4 simulated; the percentage difference is computed using the benchmark 1 as base.

The possibility to introduce components orders when the workload of the manufacturing system is low allows obtaining a more uniform utilization of the manufacturing system. Moreover, the proposed approach 2 improves this performance over 10% compared to the approach 1.

The analysis of the numerical results reveals that:

– the dynamic evaluation of the threshold level of the proposed buffers allows to improve drastically the delay performance with a more uniform distribution of the components provided to the assembly stage. Moreover, the utilization of the manufacturing system is more uniformly;
– the increments of the WIP (in particular, buffer level of the assembly stage) support the performance improvement. The only parameter ("K") can be used to

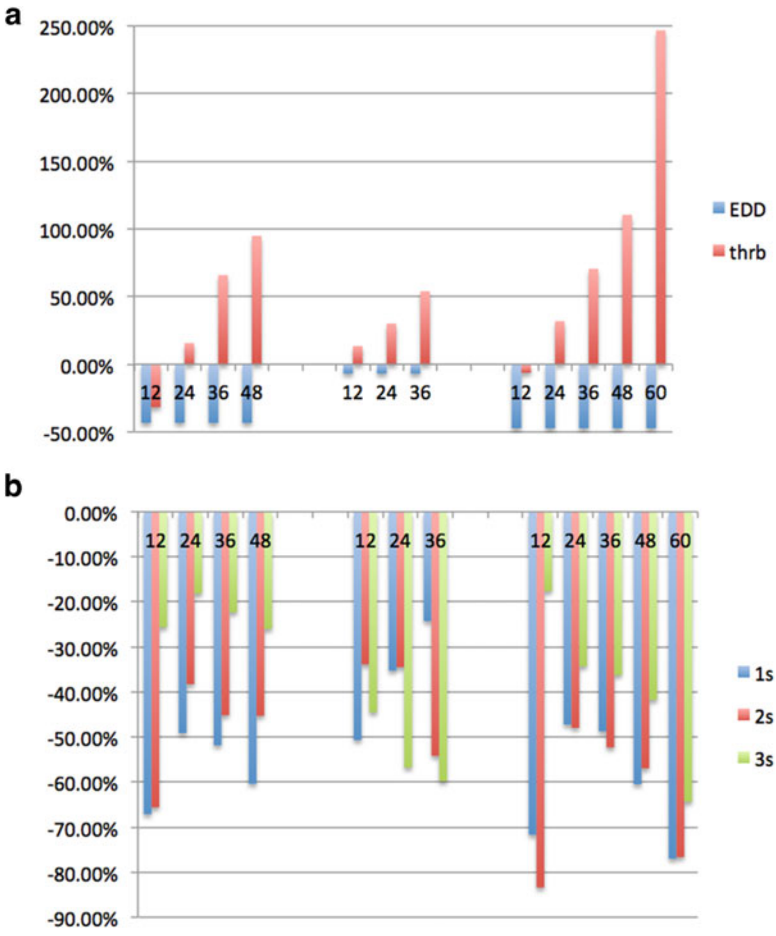

Fig. 7 (**a**) Buffer standard deviation comparison *Approach 1 (thrb)* and EDD vs. Benchmark 1. (**b**) Buffer standard deviation comparison approach 2 vs. thrb

control the better trade-off between the costs and the improvement of the production performance.
- the proposed approach can be adapted to different demand profiles without setting or changing any parameters of the control policy.

7 Conclusions

The chapter addresses the problem of the order release in an assembly job-shop to improve business performance and sustainability and proposes a decision model founded on two approaches.

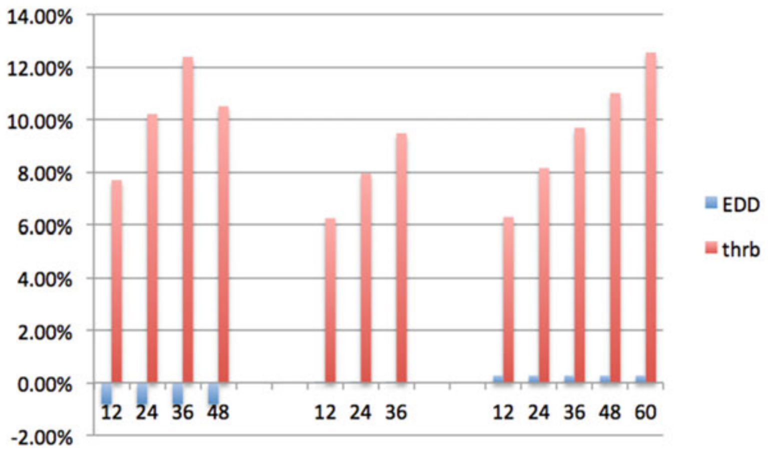

Fig. 8 Manufacturing utilization comparison approach 1, EDD vs. benchmark 1

Table 4 Manufacturing utilization—standard deviation

Benchmark	EDD	Approach 1	Approach 2
0.0743	0.0763 (+2.69%)	0.0582 (−21.67%)	0.0503 (−32.30%)

The two approaches are based on the workload control policy and allow to introduce some production orders of components when the customer demand reduces and the production systems utilization is low. The rationale behind the approaches is to make available some components in advance, to improve the manufacturing utilization during the planning horizon, to guarantee a uniform consumption of the components in the assembly stage and to assure customer satisfaction.

The chapter proposes, then, a novel model to deal with the decision of order release in an assembly job-shop. More generally, the study provides fresh insights that can be summarized as follows:

– the combination of the WLC policy with a control that inputs orders of components when the manufacturing workload is low allows to improve the performance of the customer. However, it also increases the WIP of the assembly job-shop. The study suggests the use of a single parameter to set "*K*" that allows setting the trade-off between the customer performance and the increment of buffer levels in the assembly stage;
– the proposed policy can be adapted to different demand profiles (in terms of demand arrivals and composition of the production orders) with any parameters to change;
– from the sustainability viewpoint, the proposed model allows to improve the average utilization and, then, to reduce the energy consumption during the idle time of the machine; moreover, the lower level of the WIP reduces the inventory costs of the items.

– the proposed model uses a limited amount of information and it is characterized by a low computational workload; these features corroborate the usability of the proposed model in industrial cases.

Further developments of the research concern the fact that the parameter K can be related to the costs of delay and holding in buffer, by the development of a fuzzy engine. Moreover, the decision model has to be implemented and evaluated in several industrial cases.

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Multicriteria Methodology for Assessing the Financial Performance of Sustainable Companies: The Case of Greece

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Abstract The research concerning the relation among environmental, social, and governance (ESG) criteria and corporate financial performance (CFP) can be traced back to the early 1970s. Nowadays, this relationship is of great interest as it concerns investors, banks, corporate stakeholders, and many others. In Greece, ESG has attracted recently considerably interest among financial institutions, and large companies are increasingly taking initiatives to introduce ESG criteria in their business models. In this article, we present financial analysis results for a sample of 29 large Greek companies that are considered sustainable, using 10 financial indicators. Moreover, the financial performance of the companies is evaluated through the PROMETHEE II multicriteria method.

Keywords ESG performance · Corporate social responsibility · Financial performance · Multicriteria analysis

1 Introduction

Over the past decades, corporate social responsibility (CSR) has become increasingly important. The academic and business worlds are approaching this issue with new, more improved approaches, as the basic idea of CSR was developed right after World War II. Over time, CSR approaches have adopted a more practical

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perspective, with ESG emerging as new framework based on measurable approach to corporate sustainability.

ESG is widely known as the three most important pillars of a company's sustainability, referring to environmental, social, and governance factors. These three factors cover a wide range of issues that are not traditionally part of financial analysis but may be of financial importance. In the last half of 2020, we saw a serious remit of ESG issues to the corporate agenda. In the course of the lockdown, companies immediately focused on navigating the enormous challenges of the crisis, struggling to stay afloat and adapt to work remotely. Throughout this effort, large companies turned their attention to ESG.

The number of companies using sustainability strategies that disclose ESG information continues to grow, which has led to fundamental changes in business models and management practices. The shareholder-based contract management aims at enhancing financial performance and maximizing shareholder benefits. Alternatively, a sustainable business promotes stakeholder management, which contemplates all stakeholders, encompassing shareholders, consumers, customers, communities, and other pertinent groups.

ESG criteria are now considered important factors for decision-making within a company as they are related to its financial performance. Thus, it is no surprise that major rating agencies have paid close attention to the development of ESG indicators that approach companies' best performance on non-financial assets as investors perceive an increasing awareness of this issue.

The literature on the relationship between CSR and financial performance leads to three different conclusions. Some research indicates that CSR has a positive effect of corporate financial performance (CFP), implying that companies with socially responsible practices can have better financial results than other companies that are not considered socially responsible. For example, as Porter has argued (Ambec et al., 2011), environmental factors are a source of innovation that generates additional revenue that can cover additional costs. On the other hand, these activities incur additional costs caused by organizational problems and inefficient allocation of resources, which will put the company at a disadvantage in the free and competitive market, thus leading to CSR having a negative impact on CFP. Finally, in addition to positive and negative relationships, a neutral relationship has also been found (McWilliams & Siegel, 2001; Moore, 2001).

Uncertainty in scientific findings leaves unanswered questions. The reasons for the failure to reach a consensus on the impact of CSR on CFP are related to several aspects. First, the wide range of CFP estimates makes it difficult to identify a general relationship on this issue. Market-based estimates are the most applied approaches (Peloza, 2009; Fatemi et al., 2018). CFP is widely assessed by accounting-based indicators, such as return on assets and return on equity (Ferrell et al., 2016). Choosing the right mechanism to effectively support corporate decision-making and policy analysis can be problematic. The often-used single estimate does not record potential CSR effects.

Second, a variety of CSR concepts and categories complicate the conclusions about the CSR -CFP relationship. CSR is a multidimensional concept. Companies have different incentives to pursue CSR strategies and use a wide range of resources, which lead to different effects on CFP. Studies focusing on different types of CSR activities may lead to different conclusions about the CSR-CFP relationship.

Third, as noted by Barnett and Salomon (2006), the relationship between CFP and CSR is neither strongly positive nor strongly negative. Studies that have found an inverted U-shaped relationship between CFP and environmental performance also provide evidence for the non-linear relationship (Fujii et al., 2013).

In the present study, we examine the financial performance of sustainable Greek companies, and then with the help of the PROMETHEE II method, a ranking is created from the best company in financial performance to the least profitable.

The rest of the paper is organized as follows. Section 2 describes the multicriteria methodology used in the analysis. Section 3 presents the data and the evaluation criteria (financial ratios), whereas Sect. 4 focuses on the results. Finally, Sect. 5 concludes the paper and outlines some future research directions.

2 Multicriteria Evaluation Approach

The goal of multicriteria analysis is to support decision-makers by providing some tools to enable them to advance in solving a decision problem where several often-conflicting points of view must be taken into consideration. Multi-criteria analysis methods are presented in the following four categories (Pardalos et al., 1995):

1. Multi-attribute utility theory,
2. multi-objective mathematical programming,
3. outranking relations approach,
4. preference disaggregation approach.

In this study we employ the PROMETHEE II outranking method. The family of PROMETHEE methods is one of the most popular approaches for multicriteria decision aiding, with numerous applications in various areas (Brans & de Smet, 2016; Behzadian et al., 2010). The PROMETHEE II method relies on pairwise comparisons between a set of alternatives and leads to a complete ranking from the best to the worst ones.

Formally, let $A_1, A_2, \ldots, A_m$ be m alternatives, evaluated over n evaluation criteria $g_1, g_2, \ldots, g_n$, and let y_{ik} denote the performance data for alternative A_i with respect to criterion g_k. We will assume, without loss of generality that all criteria are to be maximized.

The pairwise comparisons between the alternatives are based on the computation of a preference index $p_k(A_i, A_j)$, which represent (on a 0–1 scale) the level of preference for alternative A_i over A_j according to criterion g_k:

$$p_k(A_i, A_j) = \begin{cases} 0 & \text{if } y_{ik} \le y_{jk} \\ f_k(y_{ik} - y_{jk}) & \text{if } y_{ik} > y_{jk} \end{cases} \quad (1)$$

where $f_k(y_{ik} - y_{jk})$ is an increasing function of the difference in the performance of the alternatives. In this study, the Gaussian preference function is employed (see other types of preference functions, see (Brans & de Smet, 2016)):

$$f_k(y_{ik} - y_{jk}) = 1 - e^{-\frac{(y_{ik} - y_{jk})^2}{2s_k^2}} \quad (2)$$

where $s_k > 0$ is a user defined parameter that represents the width of the Gaussian function.

The overall preference for alternative A_i over A_j considering all criteria is derived as a weighted average of the partial preference indices, i.e.:

$$\pi(A_i, A_j) = \sum_{k=1}^{n} \omega_k p_k(A_i, A_j) \quad (3)$$

On the basis of these pairwise comparisons among of alternatives, a ranking of the alternatives from the best one to the worst one, can be obtained by considering the strengths and weaknesses of an alternative compared to all of its peers. The strengths are measured through the total preference for alternative A_i over all other alternatives. Similarly, the weaknesses of A_i are measured by summing up all preference indices $\pi(A_j, A_i)$ for all alternatives with $j \neq i$. This leads to the following net flow index:

$$\Phi(A_i) = \frac{1}{m-1} \sum_{j \neq i} [\pi(A_i, A_j) - \pi(A_j, A_i)]$$

On the basis of their net flows, the alternatives can be ranked from the best to the worst one. More specifically, if $\Phi(A_i) = \Phi(A_j)$, then A_i is indifferent to A_j, whereas if $\Phi(A_i) > \Phi(\mathrm{A_j})$, the A_i is preferred to A_j.

3 Data and Financial Performance Criteria

The sample used includes large Greek companies from various sectors (except banking), which apply ESG criteria, as listed in Table 1. The data for the analysis were collected from the balance sheets of these 29 sustainable Greek companies for the year 2019.

The purpose of financial analysis is to assess the solvency, liquidity, and profitability of companies, through the examination of various financial ratios that

Table 1 The companies in the sample

Company name	Sector	Company name	Sector
Alumil	Metal production	Mitsis	Hotels
Public Power Corporation (PPC)	Energy	Motor Oil	Oil and gas
Public Gas Corporation (DEPA)	Energy	Mytilineos	Industrial conglomerate
ElvalHalcor	Metal production	OPAP	Sports betting
Enel	Energy	Hellenic Telecommunications Organization (HTO)	Telecommunications
Eunice Trading	Energy	PAEGAE	Logistics
European Reliance	Insurance	Polyeco	Waste management
Genesis Pharma	Pharmaceutical	Quest Holdings	Information technology
Hellas Gold	Mining	Terna Energy	Energy
Hellenic Petroleum	Oil and gas	Titan	Cement production
Heracles	Cement production	Toyota Hellas	Automotive distribution
Hygeia	Health services	Uni-Pharma	Pharmaceutical
Imersys	Mining	Volterra	Energy
Megadis	Hygiene products	Volton	Energy
Merck	Healthcare research		

quantify the financial situation of a company. In this study, we consider 10 financial ratios as described below (Zopounidis, 2013).

1. *Asset turnover* (AT): it indicates how intensively a company uses its assets to generate revenue.

$$\text{Turnover}/\text{Total assets}$$

2. *Equity turnover* (ET): it indicates whether the equity is employed in an efficient manner to generate revenue.

$$\text{Turnover}/\text{Equity}$$

3. *Financial profitability* (FP): it shows whether the goal of achieving a satisfactory result for shareholders has been achieved (i.e., return on equity).

$$\text{Net profit after taxes/Equity}$$

4. *Industrial profitability* (IP): it measures the operational profitability of a firm and its ability to use its assets in efficient manner for generating strong operating profits (i.e., return on assets).

$$\text{Earnings before interest and taxes/Total asset}$$

5. *Total debt capacity* (TDC): it represents the ratio between the liabilities and the assets of the company, with higher values indicating a heavy debt burden.

$$\text{Total liabilities/Total assets}$$

6. *Long-term debt capacity* (LDC): in contrast to the TDC ratio, LDC focuses on reliance of a company on long-term debt to finance its activities, in relation to the total long-term capital sources (i.e., equity and long-term debt).

$$\text{Equity}/(\text{Equity} + \text{Long} - \text{term liabilities})$$

7. *Current ratio* (CR): it is a liquidity indicator indicating the ability of a company to cover its short-term liabilities through its current assets.

$$\text{Current assets/Current liabilities}$$

8. *Quick ratio* (QR): it extends the CR by excluding inventories from the measurement of a company's liquidity status, because inventories often do not generate cash in a timely manner to cover short-term obligations.

$$(\text{Current assets} - \text{Inventories})/\text{Current liabilities}$$

9. *Working capital ratio* (WC): this ratio indicates the ability of a firm to cover its fixed assests through long-term sources of capital (long-term liabilities and equity).

$$(\text{Equity} + \text{Long} - \text{term liabilities})/\text{Net fixed assets}$$

10. *Financial expenses ratio* (FE): this last ratio represents the burden that a company faces due to finance expenses in relation to its turnover income.

Table 2 The financial ratios data for the companies in the sample

Company	AT	ET	FP (%)	IP (%)	TDC (%)	LDC (%)	CR	QR	WC	FE (%)
Alumil	0.88	5.47	5	2	84	66	0.65	0.32	0.48	4
DEPA	0.48	0.84	8	3	43	100	2.23	2.19	10.00	0
Elval Halcor	1.17	2.69	6	5	57	58	2.11	1.06	1.61	1
Enel	0.10	0.41	−16	−3	72	43	0.80	0.78	0.86	38
Eunice Trading	1.11	2.35	−14	−1	53	95	1.56	1.54	2.30	0
Genesis Pharma	0.91	1.88	13	11	52	87	1.75	1.56	2.43	0
Hellas Gold	0.11	−3.38	−100	−5	103	−16	0.08	0.05	0.20	23
Heracles	0.40	0.72	2	2	45	73	1.04	0.80	1.01	1
Imersys	0.58	1.40	0	−1	58	52	1.59	1.04	1.16	8
Merck	1.32	4.84	10	4	72	100	1.39	1.11	10.00	0
Mitsis	0.20	0.49	4	2	59	57	0.75	0.75	0.90	7
Motor Oil	2.91	6.84	20	11	55	63	1.85	1.31	1.49	0
Mytilineos	0.54	1.38	9	8	61	54	1.59	1.40	1.29	2
HTO	0.61	1.79	2	1	66	55	0.82	0.80	0.90	2
Polyeco	0.60	0.82	15	15	26	90	3.28	3.16	1.96	1
Quest Holdings	1.42	4.19	6	7	66	69	1.18	1.04	1.23	1
Terna Energy	0.12	0.27	7	0	56	49	1.85	1.80	1.09	15
Titan	2.24	3.08	11	12	27	78	1.73	0.83	1.06	5
Toyota Hellas	2.54	4.90	23	16	47	100	1.56	0.96	1.92	0
Uni-Pharma	0.41	1.02	9	5	59	59	0.91	0.39	0.95	2
Volterra	0.12	0.29	3	1	59	47	1.29	1.29	1.03	27
Volton	0.90	8.77	30	4	89	26	1.21	1.21	1.44	1
PPC	0.37	1.76	−73	−18	72	31	0.64	0.48	0.81	4
Hellenic Petroleum	1.24	3.58	14	5	63	55	1.19	0.79	1.07	1
European Reliance	0.54	0.71	13	14	24	96	3.92	3.92	4.37	0
Megadis	1.43	4.36	20	9	67	57	1.14	0.84	1.12	2
OPAP	1.99	5.79	26	12	66	40	2.66	2.64	1.40	1
Paegae	0.15	0.16	4	5	5	97	5.00	5.00	1.34	0
Hygeia	0.46	0.81	19	9	43	67	2.17	2.14	1.27	3

$$\text{Financial expenses/Turnover}$$

Table 2 presents the data of the 29 companies in the sample on the above financial ratios.

4 Results and Discussion

For the application of the PROMETHEE II method on the data set under consideration, equal weights were used for all financial ratios, whereas the width of the Gaussian preference functions for the criteria was set equal to the mean absolute deviations of the financial ratios.

Table 3 presents the evaluation results with the companies ranked in descending order in terms of their net flows obtained through the PROMETHEE II method. The company with the strongest financial performance in the considered sample is European Reliance, with a net flow of 0.4494. Its good performance can be verified from Table 2 where the company presents particularly good results on all financial ratios. The second best company is Toyota Hellas, closely followed by Polyeco. OPAP (0.3108) is fourth in the ranking, with satisfactory performance on most of the financial ratios except long-term dept. capacity, where its performs moderately. Of course, financial profitability, as well as capital turnover ratios, seem to be relatively low compared to the top three companies. Fifth is PAEGAE (0.2817) with less good performance than the above companies as the total and long-term debt capacity, current ratio, quick ratio, working capital, and financial expenses give satisfactory results for the company. These ratios show the effective use of its assets and capital to help generate revenue. Also, the company can meet its obligations to a large extent. On the contrary, its financial and industrial profitability is at a low level, which indicates low shareholder return performance as well as low sustainable activity. The company also has medium performance in terms of its debt burden and the current ratio.

Regarding the worst performing companies, Mitsis (−0.2293) ranks 25th. The low performance in the capital turnover ratios shows that the company does not

Table 3 Evaluation results (net flows)

Company	Net flow	Company	Net flow
European Reliance	0.4494	Hellenic Petroleum	−0.0036
Toyota Hellas	0.3599	Volton	−0.0137
Polyeco	0.3569	Mytilineos	−0.0436
OPAP	0.3108	Heracles	−0.1035
PAEGAE	0.2817	Alumil	−0.1510
Motor Oil	0.2795	Uni-Pharma	−0.1530
DEPA	0.2332	Imersys	−0.1724
Titan	0.2317	HTO	−0.1844
Merck	0.2104	Terna Energy	−0.1935
Genesis Pharma	0.1757	Mitsis	−0.2293
Hygeia	0.1208	Volterra	−0.2803
Megadis	0.0639	PPC	−0.4377
Quest Holdings	0.0490	Enel	−0.4626
Eunice Trading	0.0366	Hellas Gold	−0.7654
Elval Halcor	0.0345		

intensively use its assets and equity to generate revenue. Finally, although the company is dealing with liquidity issues, its debt ratios appear to be at low levels. A similar situation is faced by the next company, Volterra (−0.2803), which ranks 26th. PPC (−0.4377) ranks 27th, as company performs well only on the equity turnover ratio. Enel (−0.4626) also performs poorly on most financial ratios, thus leading to a low overall CFP. Finally, Hellas Gold (−0.7654) ranks last, suffering from very poor performance on all financial ratios.

In conclusion, what we have observed is that companies that follow the principles of ESG in Greece appear to face similar financial challenges with other (non-ESG) companies. A company implementing ESG strategies, does not necessarily mean that these strategies will be financially sound. Businesses now need to introduce ESG criteria and in combination with the financial capabilities of each company to make decisions. From the above results, we could not conclude anything different from the fact that even ESG companies can have low financial performance as well as these are organizations that have operations and strategies that may or may not be profitable.

5 Conclusions and Future Directions

This research was conducted to find out if companies that use ESG indicators are considered sustainable if they have satisfactory financial performance. This is a major issue nowadays and many researchers have given different interpretations on the relationship between ESG and corporate financial performance.

In this research, 29 Greek companies that follow the principles of ESG were evaluated across 10 financial ratios. The evaluation was performed with the PROMETHEE II multicriteria method. Such an evaluation could be of interest to various stakeholders and actors who are interested in the financial materiality of adopting the principles of ESG. Among others, these include shareholders, corporate management, as well as private and institutional investors.

Given that ESG is an active area of research with strong practical interest, various future research directions could be explored. First, the causal relationship between ESG and CFP strategies should be examined to clarify what kind of efforts companies should make to strengthen their financial performance by adopting good and sustainable business practices. In addition, it would be interesting to compare the financial performance of companies adopting ESG to companies that do not follow the principles of ESG. Moreover, it would be relevant to examine the results for different sectors of companies and over time, as well as to integrate ESG and CFP into a holistic framework for assessing corporate performance. Finally, it is important to highlight the need for implementing and adopting common ESG reporting standards, which will greatly improve the availability of ESG data, thus allowing for more elaborate research to be conducted.

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