Development and application of IT-supported collaborative planning methods considering uncertainty for advising sustainable development

Cumulative dissertation to obtain the doctoral degree (Dr.nat.techn.)
at University of Natural Resources and Life Sciences, Vienna (BOKU)

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09/2021

“The significant problems we have cannot be solved at the same level of thinking with which we created them“

--- Albert Einstein ---

Abstract

The world is facing several deep and interconnected crises leading to undesired and irreversible consequences for large parts of the world, which makes a transition to a global sustainable development path inevitable. Collaborative planning methods supporting such a transition have to be better understood with respect to their methodological properties. Furthermore, the systematic identification and consideration of different uncertainty issues within the solving process of wicked sustainability problems is a scientific question of high interest, as the understanding of the uncertainty's impact is crucial for the decision quality.

Hence, this thesis is concerned with the development and application of collaborative planning methods, in particular with two well-known IT-supported multi-criteria decision making techniques, namely with the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP). Two different sustainability problems referring one to the micro level perspective and the other one to the macro-level perspective are considered. Uncertainty is addressed with the application of two different approaches, embracing firstly a broad-scale sensitivity/uncertainty analysis and secondly the application of multiple models to a single case as part of a multi-method approach. Additionally, these analyses are supplemented by two literature reviews, a multi-criteria assessment of reviewed methods analyzing SDG (target) entity interactions and by supporting a framing of methodological results as a typical advice.

The systematic literature review regarding methods analyzing SDG (target) entity interactions led to the identification of a broad range of 30 methods applied in 93 analyzed scientific publications published from 2015 to the end of 2019. The evaluation of these methods indicates several differences with respect to their methodological properties. In particular, primarily the methods relating to the quantitative categories (Simulation, Other quantitative and Statistical) can develop a statement regarding the involved uncertainty's impact. The critical literature review aiming to provide an overview of uncertainty issues associated with the application of the Analytic Hierarchy Process allowed identifying 12 related uncertainty issues.

The IT – supported application of the broad scale simulation experiment to the sustainability problem on the micro-level aimed to analyze the impact of different uncertainty scenarios in using the Analytic Hierarchy Process. The results showed that in about 50% of the simulation runs rank reversals occurred compared to the cases neglecting uncertainty. The maximum numerical impact on an alternative's evaluation caused by an uncertainty scenario is very small (approximately 0.03). The application of multiple models to the sustainability problem at the macro-level showed that the Analytic Network Process validates both SDG target rankings initially based on the cross-impact matrix in terms of approving the best ranked SDG target, which indicates that these rankings are robust.

Finally, it can be concluded that solving wicked sustainability problems supporting the transition to a global sustainable development path have to go through the three phases of collaborative planning repeatedly using multiple methods and / or multi-method applications for these different phases while considering meta-choices, such as the integration of uncertainty issues.

Keywords: Sustainable development, Sustainable development goals, collaborative planning, multi-criteria decision making, Analytic Hierarchy Process, Analytic Network Process, uncertainty assessment, advice formulation

Zusammenfassung

Die globale Gemeinschaft ist mit multiplen, vernetzten und tiefgreifenden Krisen konfrontiert, die unerwünschte und unumkehrbare Folgen für große Teile der Welt mit sich bringen. Folglich ist eine Transformation zu einer globalen nachhaltigen Entwicklung unvermeidlich. Kollaborative Planungsmethoden können helfen diese Transformation zu unterstützen, jedoch bestehen Lücken im Verständnis ihrer methodischen Eigenschaften und somit auch hinsichtlich ihres optimalen Anwendungsbereichs. Darüber hinaus, spielt die systematische Identifizierung und Berücksichtigung von Unsicherheitsaspekten eine große Rolle im Lösungsprozess von „unstrukturierten" Nachhaltigkeitsproblemen, da ihr Verständnis einen wesentlichen Einfluss auf die Qualität der Entscheidung hat.

Folglich, widmet sich diese Dissertation der Entwicklung und Anwendung von kollaborativen Planungsmethoden. Der Fokus liegt auf den etablierten und IT-gestützten Methoden Analytischer Hierarchie Prozess (AHP) und Analytischer Netzwerk Prozess (ANP), welche zur Klasse der multi-kriteriellen Entscheidungsfindungsmethoden zählen. Zwei unterschiedliche Nachhaltigkeitsprobleme (Mikro- und Makro-Level) werden detailliert analysiert. Unsicherheitsaspekte werden mittels zwei unterschiedlicher Ansätze berücksichtigt: 1) eine Querschnitts-Sensitivitäts-/Unsicherheitsanalyse und 2) Berechnung mehrerer Entscheidungsmodelle für einen Anwendungsfall im Kontext eine multi-Methodenapplikation. Zusätzlich werden diese Analysen durch zwei Literatur-Reviews unterstützt, wobei einerseits eine multi-kriterielle Evaluierung von Analysemethoden von Interaktionen von SDG (Subziel) Entitäten sowie eine Übersetzung methodischer Ergebnisse in verständliche Ratschläge durchgeführt worden ist.

Der systematische Literatur-Review zur Identifizierung von Analysemethoden von Interaktionen von SDG (Subziel) Entitäten resultierte in einer großen Bandbreite an 30 Methoden die in 93 wissenschaftlichen Veröffentlichungen aus den Jahren 2015 bis inklusive 2019 publiziert wurden. Die Evaluierung dieser Methoden belegt ihre unterschiedlichen Potenziale und Schwächen im Hinblick auf ihre Anwendung. Im Besonderen, Methoden der quantitativen Kategorien (Simulation, Andere Quantitative und statistische Methoden) erlauben die Darstellung des Einflusses von Unsicherheitsaspekten auf das Ergebnis.

Basierend auf dem kritischen Literatur-Review wurde ein Überblick über die wesentlichen Unsicherheitsaspekte im Kontext einer Anwendung des Analytischen Hierarchie Prozesses erstellt, welcher 12 Aspekte klassifiziert. Die computergestützte Anwendung des Querschnitts-Simulationsexperiments auf das Nachhaltigkeitsproblem des Micro-Levels zielte darauf ab unterschiedliche Unsicherheits-Szenarien im Kontext einer Anwendung des Analytischen Hierarchie Prozesses zu analysieren. Die Ergebnisse zeigen, dass rund 50% der Simulations-Durchläufe eine andere best-gereihte Alternative aufweisen als jene Fälle, die keine Unsicherheitsaspekte berücksichtigen. Der maximale numerische Einfluss eines Unsicherheits-Szenarios auf die finalen Prioritäten ist - unter Berücksichtigung aller Entscheidungsalternativen - klein und kann mit rund 0.03 beziffert werden. Die Berechnung mehrerer Modelle für das Nachhaltigkeitsproblem des Makro-Levels zeigte, dass der Analytische Netzwerk-Prozess die bestgereihten SDG Subziele zweier Rankings bestätigt, die auf der Berechnung mittels Wirkungsmatrix beruhen. Folglich sind diese Ergebnisse validiert und somit robust.

Es kann geschlussfolgert werden, dass das Lösen von „unstrukturierten“ Nachhaltigkeitsproblemen, welche die Transformation zu einer globalen nachhaltigen Entwicklung fördert, alle drei Phasen des kollaborativen Planens iterativ durchlaufen muss. Dies kann nur unter der Anwendung von unterschiedlichen Methoden und / oder von multi-Methodenapplikationen in allen Phasen des kollaborativen Planens und unter Berücksichtigung von Meta-Entscheidungen, wie z.B.: die Integration von Unsicherheitsaspekten erfolgen.

Schlüsselwörter: Nachhaltige Entwicklung, Ziele nachhaltiger Entwicklung, Kollaboratives Planen, Multi-kriterielle Entscheidungsfindung, Analytischer Hierarchie-Prozess, Analytische Netzwerk-Prozess, Evaluierung von Unsicherheit, Beratung

Acknowledgements

My doctoral study can be described as long and wonderfully inspiring journey. It also involved several phases of doubts and thoughts concerned with cancelling my studies due to lacking financial support. However, this thesis is evidence that personal persistence as well as multi-facetted received support from different people can lead to a very satisfying result.

I want to express my deepest gratitude to my supervisor Ao.Univ.Prof. DI Dr. Harald Vacik who always supported me to find my way to finish my doctoral study. Additionally, I am very thankful for his mentoring, his encouragement to research on tricky methodological questions supplemented by his outstanding research experience in this context and his never-ending patience, which all together will serve as great inspiration for my future.

I am very much grateful to Mareike, who backed my decision to work intensively on my thesis and her encouragement to go step by step until it's finished while suffering having too less time with me. I want to express my deep gratitude to my parents who have taught me to be curios on how things work and their constant believe in me.

I would like to express my sincere thanks to my co-supervisors Dr. Helga Pülzl and Ao.Univ.-Prof. Dr. Helmut Haberl for their continuous guidance of my doctoral study. Finally, I am very thankful to my close friends for lending me their ear whenever some issues wanted to be heard or discussed and for helping me to believe that this journey is one that can be accomplished.

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Acronyms

Abbreviation	Meaning
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CI-matrix	Cross-impact matrix
MCDM	Multi-criteria decision making
PT	Preference tendency
SD	Sustainable development
SDG	Sustainable development goal
US	Uncertainty scenario

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1 General Introduction

1.1 Background

1.1.1 Sustainable Development and its goals

The world is facing four deep and interconnected environmental crises: the human-induced climate change, unsustainable land use, mega-pollution, and increased frequency and intensity of pandemic zoonotic diseases (Sachs & Sachs, 2021). The referring arising global environmental change is going to lead to undesired and irreversible consequences for large parts of the world which makes a transition to a global sustainable development (SD) path inevitable (Brandi, 2015; Rockstrom et al., 2009). Several understandings of SD are still discussed, however in its core sustainability is concerned with the long-term development of interlinked human-environment systems embracing an economic, a social and an environmental dimension (Scholz & Binder, 2011; UN, 1987).

The necessity for a global transition is reflected by the UN's resolution regarding the SD Agenda for 2030. The fundamental aim of the 2030 Agenda is to transform the world to a sustainable development path while leaving no one behind (UN, 2015), and this ethos is fundamentally linked to the Agenda's two key principles: universality and indivisibility. Universality implies that the Agenda applies to all nations regardless of their levels of income. Indivisibility means that the formulated 17 Sustainable Development Goals (SDGs) (see Table 1) and 169 targets relating to these goals should be implemented as an 'indivisible whole'. This interconnected nature of the SDGs is seen as axiomatic, even though the connections between the goals are uneven or that economic growth is prioritized over ecological integrity (Eisenmenger et al., 2020; McGowan, Stewart, Long, & Grainger, 2019). Nevertheless, the Agenda does mark a major transformation from rule-based to goal-based governance of global sustainability and where coordinated action is required for success (Biermann, Kanie, & Kim, 2017; Kanie et al., 2019).

Table 1: Overview of SDGs adapted from United Nations (2015)

SDG	Title
1	End poverty in all its forms everywhere
2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3	Ensure healthy lives and promote well-being for all at all ages
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	Ensure availability and sustainable management of water and sanitation for all
7	Ensure access to affordable, reliable, sustainable and modern energy for all
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10	Reduce inequality within and among countries
11	Make cities and human settlements inclusive, safe, resilient and sustainable
12	Ensure sustainable consumption and production patterns
13	Take urgent action to combat climate change and its impacts
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Based on the UN’s focus on ‘the indivisible whole approach’ of the SDGs, the 2030 Agenda should be implemented in an integrated and coherent manner (Breuer, Janetschek, & Malerba, 2019; UN, 2015), which makes it necessary to understand the type of problem that is to solve.

1.1.2 Sustainability problems

Sustainability problems are representative of so-called wicked problems (Walters, Balint, Stewart, & Desai, 2011), which embed several characteristics (Assuad, 2020; Dovers, 2005; Eden & Wagstaff, 2020; Sediri, Trommetter, Frascaria-Lacoste, & Fernandez-Manjarres, 2020):

1) 'ill-defined' as there are various and competing stakeholders' narratives and framings of what is the problem to solve
2) extended temporal and spatial scales of impacts in environmental systems
3) highly complex connections between issues; especially global natural phenomena are linked in cause and consequence
4) high level of uncertainty of consequences of human intervention in environmental systems and poor-quality information about the state of these systems
5) need for multi-stakeholder collaboration and community participation
6) scale mismatches concerning spatial, temporal and institutional processes

Sustainability problems cannot be solved in a classical sense as they are resistant to a definite solution. The implemented solution will impact the interlinked human-environment system which then accordingly will change the definition of the problem (Eden & Wagstaff, 2020; Sediri et al., 2020). Any political solution such as the implementation of the SDGs on national level is dependent upon the integration of scientific knowledge, although the science policy interface shows barriers and gaps while a respective new paradigm is emerging (Klauer, Manstetten, Petersen, & Schiller, 2013; Martínez-Fernández, Banos-González, & Esteve-Selma, 2021; Weichselgartner & Kasperson, 2010). Therefore, planning targeting solving sustainability problems has to cope with a tremendous complexity arising from human-environment interaction. Solving sustainability problems is multifaceted and often involves several stakeholders with varying levels of power and different objectives, which cannot be satisfied simultaneously. Furthermore, planning typically uses knowledge from several disciplines incorporating natural, physical, and social sciences as well as medicine, politics, and ethics. In the process of planning, important information may be lost, competing values may be discarded, and elements of uncertainty may be ignored. Hence, many decisions regarding SD bring along unintended consequences that are not reflected in the planning process (Dietz, 2003; Harding, Hendriks, & Faruqi, 2009; Kiker et al., 2005; Scholz & Binder, 2011).

The implementation of the 2030 Agenda as an ‘indivisible whole’ (UN, 2015) clearly demonstrates a major characteristic of sustainability problems, in particular that different goals cannot be satisfied simultaneously. Current research recommends to identify such tensions of different SDGs and to address these trade-offs as crucial elements that might counteract the overall implementation (Bowen et al., 2017; Lusseau & Mancini, 2019). In this context, a huge variety of approaches were developed to conceptualize and to measure SDG target interactions (Bennich, Weitz, & Carlsen, 2020), but science is still asked to develop ‘new’ methods and tools to identify and to quantify SDG target interactions as well as monitoring mechanisms (Allen, Metternicht, & Wiedmann, 2021; Lu, Nakicenovic, Visbeck, & Stevance, 2015).

1.1.3 Collaborative planning

The creation of accepted and sound answers to sustainability problems requires the inclusion of several stakeholders and thus collaborative planning. Vacik et al. (2014, 305) structure the collaborative planning process into three general phases (see Table 2) embracing problem identification, problem modelling and problem solving.

Table 2: Phases of collaborative planning

General Phase collaborative planning	Characteristic
Problem identification	involves the acquisition and analysis of information to understand and to define the different decision problems by identifying goals and objectives, management alternatives, related policies, resources, conflicts and interactions
Problem modelling	involves model building to represent both the relations between management options and outcomes of interest(s) of stakeholder groups and the management policy scenarios
Problem solving	involves the design of management plans with prioritizing options and determines the implementation process

As shown by Vacik et al. (2014), various methods with different pros and cons were used for collaborative planning purposes in the context of programme-based planning of natural resources that time. However, current collaborative planning activities in the context of SD focus on the implementation of the SDGs fundamentally relying on the understanding of SDG interactions. Several reviews focusing on methods and tools identifying and measuring SDG (target) interactions were published. Miola et al. (2019) analyzed 220 publications, both peer-reviewed and grey literature with respect to the distribution of targeted SDGs and the total amount of synergies and trade-offs analyzed. Bennich et al. (2020) reviewed 70 peer-reviewed articles and mapped (i) policy challenges typically addressed, (ii) ways in which SDG interactions have been conceptualized, (iii) data sources used, and (iv) methods of analysis frequently employed. Additionally, Allen et al. (2021) analyzed >150 papers including academic articles as well as grey literature and identified different science-based approaches used for four different aspects of SDG implementation. However, a systematic evaluation of the applied methods and tools properties' is missing.

1.1.4 The Analytic Hierarchy Process and the Analytic Network Process

Multi-criteria decision making (MCDM) methods are increasingly used and appear to be the most widely used approach for collaborative planning activities in the context of SD from 2010-2017. The Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) are well-known representatives of MCDM methods and often used in collaborative settings to plan and structure decisions regarding sustainability problems (Dos Santos, Neves, Sant'Anna, Oliveira, & Carvalho, 2019; Kheybari, Rezaie, & Farazmand, 2020). In particular, they were the most used MCDM methods for preference modelling (relates to phase problem modelling) and preference aggregation (relates to phase problem solving) as part of the multi-criteria decision making process considering a sample of 343 papers (Kandakoglu, Frini, & Ben Amor, 2019).

The AHP has been extensively used for ‚sustainability problems' since its inception in the 1970s (Cinelli, Coles, & Kirwan, 2014; Reichert, Langhans, Lienert, & Schuwirth, 2015; Saaty, 1977; Schmoldt, 2001; Vacik et al., 2014; Vacik & Lexer, 2001). The ANP is the generalized form of the better-known AHP and was developed in the 1990s (Saaty, 1996). The ANP has also been applied to a diverse range of areas in the last few decades but not that extensively as the AHP (Kheybari et al., 2020; Sipahi & Timor, 2010). The ANP has been applied to topics entailing all three pillars of SD. For example, the range of areas the ANP has been used in includes business and financial management topics (economic pillar), issues of environment and energy management (environmental pillar) and questions of human resources management (social pillar) (Kheybari et al., 2020).

While the AHP is centered on the decision problem in a hierarchy (see Figure 1 a)), the ANP generalizes the hierarchy into a network to better capture real-world interdependencies and processes (see Figure 1 b)) (Ishizaka & Nemery, 2013, 60). The ANP facilitates the decomposition of a decision problem into a network of its single elements to reduce the overall complexity to allow accurate evaluation. Further, the ANP provides the opportunity to consider the dependence and feedback of these elements that often arise in practical decision-making.

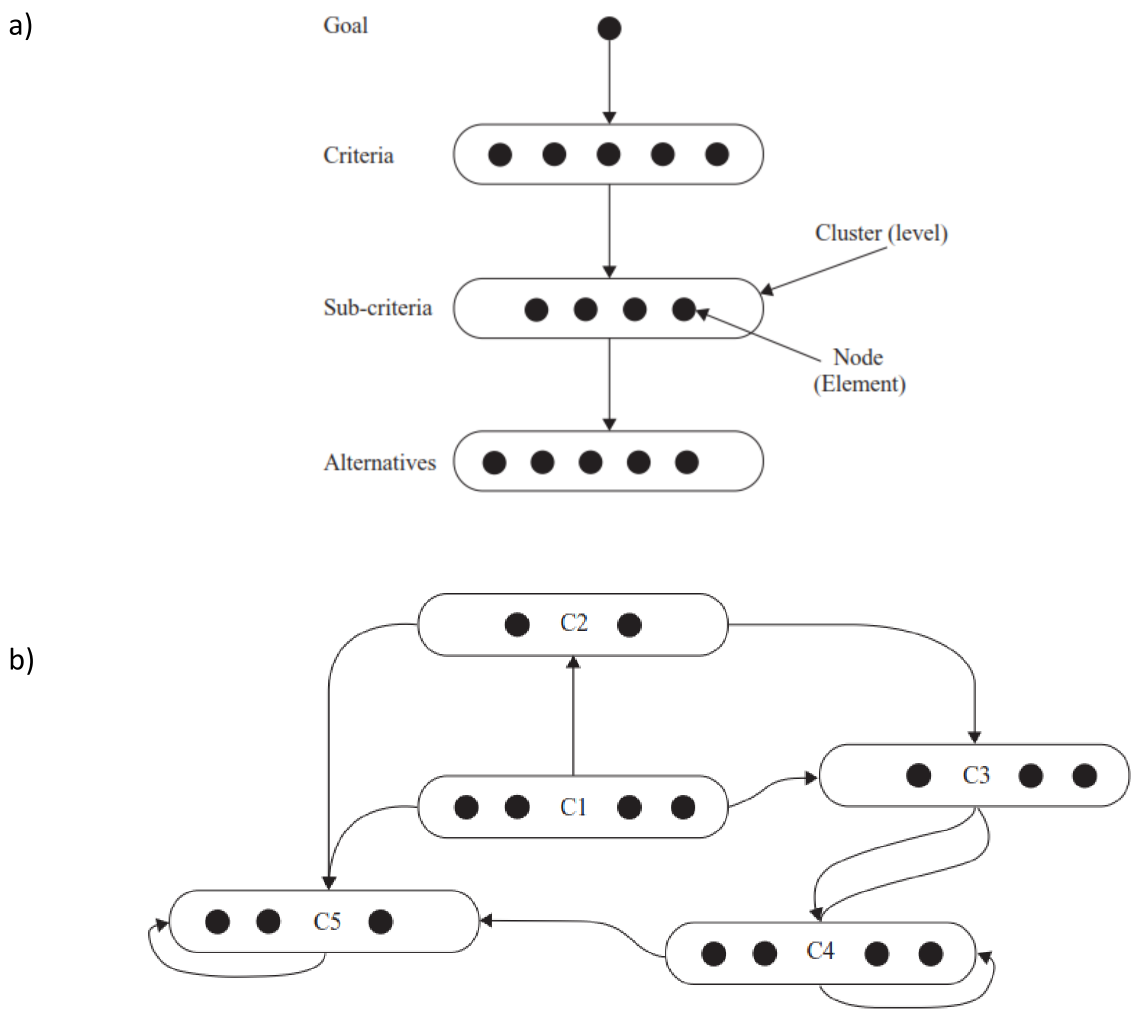


Figure 1: Comparison of decision problem modelling of a) AHP and b) ANP

Both, the AHP and the ANP are methods that are useful for all three phases of the collaborative planning process, whereas they demonstrate strengths to support problem solving compared to other collaborative planning methods (Vacik et al., 2014).

1.1.5 The role of uncertainty integration

The characteristics of sustainability problems (see section 1.1.2) bring along a tremendous complexity indicating that various sources of uncertainty exist. Ascough et al. (2008) list the uncertainty sources Variability uncertainty, Decision-making uncertainty, Linguistic uncertainty and Knowledge uncertainty. The inherent variability manifested in human-environment systems creates fundamental uncertainty (e.g., chaotic and unpredictable quality of natural processes, such as climate change). Decision-making uncertainty relates to ambiguity in quantifying social objectives in the context of ex-ante policy evaluations (e.g., quantifying the economic costs/benefits of policy changes in relation to SDG implementation). Linguistic uncertainty arises because the natural language is vague, ambiguous as well as context dependent (e.g., description of SDG targets). Finally, Knowledge uncertainty refers to the limitation of our knowledge (e.g., modelling including uncertainty in measured input data). As the different uncertainties are linked to each other (Ascough Ii et al., 2008), their systematic consideration in solving sustainability problems is critical.

The understanding and definitions of involved uncertainty in applying modelling approaches to SD areas vary with respect to different authors (Kirchner et al., 2021; Jens Christian Refsgaard, van der Sluijs, Højberg, & Vanrolleghem, 2007; Regan, Colyvan, & Burgman, 2002; Skinner, Rocks, Pollard, & Drew, 2014). However, uncertainty related to the application of MCDM methods, such as the AHP and ANP can be classified according to three dimensions proposed by Walker et al. (2003) (see Table 3) who provide a conceptual basis for the systematic treatment of uncertainty in model-based decision support. Although this publication received some criticism (Norton, Brown, & Mysiak, 2006), it seems meaningful to use its conceptual basis here for introducing the huge variety of potential uncertainty issues.

Table 3: Dimensions of uncertainty relevant for the application of MCDM methods

Dimension of uncertainty	Description
Location	The location is the part of the model (capturing the sustainability problem) where the uncertainty is generated. Five generic locations can be distinguished: 1) Context 2) Model structure uncertainty 3) Model technical uncertainty 4) System data 5) Parameter uncertainty
Level	The level of uncertainty is associated with different levels of knowledge, i.e., where the uncertainty manifests itself along the spectrum between deterministic knowledge and total ignorance. The following types are listed by the authors: 1) Statistical uncertainty 2) Scenario uncertainty 3) Recognizing ignorance 4) Total ignorance
Nature	The nature clarifies whether the uncertainty is due to the imperfection of our knowledge (epistemic uncertainty) or if it is due to an inherent variability (variability uncertainty) of the phenomena described

As presented in Table 3, uncertainty may appear in a broad range of formats, which detailed description is neglected here. For more details of the sub-dimensions of uncertainty, please refer to the original publication of Walker et al. (2003). Additionally, a lot of meta-choices (e.g., choice of which stakeholders to include or decide on the collaborative planning method) have to be made to solve a problem, whereas the involved human judgements are subject to numerous cognitive and motivational biases that introduce uncertainty (Ferretti & Montibeller, 2016; Montibeller & von Winterfeldt, 2015). Hence, the way in which human inputs are incorporated in the process of collaborative planning has to be considered carefully (Ascough Ii et al., 2008; Hofmann, 2007; Hämäläinen, 2015).

The integration of uncertainty issues plays a major role for the overall quality of the decision made and is therefore a scientific question that is of high interest (Ascough Ii et al., 2008; Walling & Vaneeckhaute, 2020). In the process of solving sustainability problems, elements of uncertainty may be ignored, which finally bring along unintended consequences that are not reflected in the process (Dietz, 2003; Harding, Hendriks, & Faruqi, 2009; Kiker, Bridges, Varghese, Seager, & Linkov, 2005; Scholz & Binder, 2011). However, the type of uncertainty characterizing the specific problem to solve may guide the selection between MCDM methods (Cinelli, Kadziński, Gonzalez, & Słowiński, 2020; Wątróbski, Jankowski, Ziemba, Karczmarczyk, & Zioło, 2019). In this context, a review showed that only some of the 23 reviewed MCDM software products allow to explicit model uncertainty (Mustajoki & Marttunen, 2017). Several methods were reported in literature to assess involved uncertainty (Jens Christian Refsgaard et al., 2007), whereas Uusitalo et al. (2015) proposed six overarching approaches to assess uncertainty of deterministic models' (e.g., MCDM models) outputs (see Table 4).

Table 4: Overarching approaches to assess uncertainty

Assessment approach of uncertainty	Description
Expert judgement	Expert judgement can be approached to assess the estimates of the variance around model parameters and also the uncertainties related to the model output. If several experts are involved, a technique for aggregating the expert's judgements needs to be chosen.
Model emulation	To reduce computational complexity to allow more re-runs for uncertainty analyses, a model emulation is built, which is a statistical low-order approximation of the original complex model. If the emulation is precise enough, it is feasible to substitute to original model and base uncertainty analyses on the model emulation. This type of uncertainty integration is usually not used for MCDM.
Temporal and spatial variability in the deterministic models	Model input data embracing observed natural phenomena show a variation over time and space. This spatiotemporal variance can be used as proxy for the uncertainty (variation) of the interest variable.

Use of multiple models	To some extent, uncertainties can be addressed by applying different models to the same domain. If the model output is very different, it is reasonable to assume that the structural uncertainty of the model(s) is large: 1) Single model ensemble: running a single model multiple times with different set of initial values 2) Multiple model ensemble: running several models with one set of initial values
Sensitivity/uncertainty analysis	The basic idea of the sensitivity analysis is to alter model input values and/or parameters of the model. If the values of the model output only change little, the modelling results are robust. The alteration can be adopting a range of approaches ranging from simple one-factor-at-a-time methods (local sensitivity analysis) to factor combinations (global sensitivity analysis), as combinations may include non-linear interactions. An uncertainty analysis is used to quantify the changes in the modelling results induced by uncertainty in input values and/or parameters.
Statistical approaches	Several statistical assessments (e.g., cross-validation or bootstrapping) analyzing the uncertainty related to the model output can be applied if enough data regarding the modelled phenomenon is available.

The application of the AHP and ANP involves several uncertainty issues as some of their methodological properties are under debate (Ishizaka & Nemery, 2013; Whitaker, 2007a, 2007b). Recent studies investigate the need for addressing uncertainty issues of the AHP (Cinelli et al., 2014; Vacik et al., 2014). More specifically, literature reveals a wide range of theoretical reflections, simulation experiments and procedural modifications of the AHP (e.g., Hung, Ma, & Yang, 2009; Ishizaka & Nemery, 2013; Levary & Wan, 1998; Ozdemir & Saaty, 2006; Paulson & Zahir, 1995; Saaty, 2010; Sadiq & Tesfamariam, 2009; Warren, 2004; Wolfslehner, Vacik, & Lexer, 2005). The authors are mostly concerned about methodological properties of the AHP that can cause uncertainty regarding the derived results. Walling & Vaneeckhaute (2020) summarize, that is important to identify and describe uncertainties, to systematically consider and generate them within the models and to assess the uncertainty of the model output. However, such a comprehensive uncertainty analysis of the AHP is missing.

1.1.6 Formulating advice

The methodological result of the application of a MCDM method is a decision alternative ranking and therefore embraces an advice which option is evaluated best. The interpretation of this advice usually requires expert knowledge as the modelling assumptions, the uncertainty conditions and the potential uncertainty integration may be difficult to understand for the decision makers. Hence, translating these methodological results into practice relevant advice is highly dependent on how methodological uncertainty is addressed which, if done well, may increase the likelihood that the advice will be taken up by decision makers (Brugnach, Tagg, Keil, & de Lange, 2007; Gilbert, Ahrweiler, Barbrook-Johnson, Narasimhan, & Wilkinson, 2018).

Many existing studies on SDG interactions have not bridged the gap of translating the methodological result into usable advice for decision making. Against this background, scientists are being asked to translate the growing understanding of SDG interactions into usable policy advice and make this knowledge readily available for policymakers (Breuer et al., 2019). To avoid 'paralysis by analysis', where the different methodological results remain unused, scientists will be challenged by the task to develop new tools and methods that satisfy policymakers' needs (Allen et al., 2021; Lyytimäki, Lonkila, Furman, Korhonen-Kurki, & Lähteenoja, 2020; Weichselgartner & Kasperson, 2010).

1.2 Problem statement

Recent sustainability problems of global scope, such as the prioritization of the implementation of SDG action have to be addressed to guarantee the necessary transition to a global SD path (Lu et al., 2015; Sachs et al., 2019). To support such a transition, collaborative planning methods applied for assessing interactions of SDG target entities (Allen et al., 2021; Bennich et al., 2020) have to be better understood with respect to their methodological properties. Furthermore, the systematic identification and consideration of different uncertainty issues within the solving process of sustainability problems using collaborative planning methods is a scientific question of high interest, as the understanding of the uncertainty's impact is crucial for the overall decision quality (Ascough Ii et al., 2008; Walling & Vaneeckhaute, 2020). Additionally, science is asked to support collaborative planning for the prioritization of SDG implementation actions with the development of new methods and multi-method applications that allow tackling the wicked characteristics of sustainability problems (Allen et al., 2021; Lu et al., 2015). Moreover, current research often lacks the orientation on policymakers' needs in terms of translating the growing understanding of SDG interactions into usable policy advice and make this knowledge readily available for policymakers (Allen et al., 2021; Breuer et al., 2019; Weichselgartner & Kasperson, 2010).

1.3 Overall aim and structure of the thesis

Responding to the problem statement (see section 1.2), the overall aim of this thesis is the development and application of IT-supported collaborative planning methods considering uncertainty for advising sustainable development. Section 2 provides an overview of the research framework including the research objectives targeted and their mapping to the publications that are part of this thesis. Section 3 presents the methodology applied whereas section 4 give insight into the results derived. Section 5 discusses the results responding to the single research questions and section 6 presents integrated conclusions with respect to the overall aim of the thesis.

2 Research framework

In Table 5 the research framework of this thesis is presented by translating the research objectives into specific research questions and by identifying the methodology applied to answer these questions. Furthermore, the declaration of authorship and the status of the publications are described.

Table 5: Research framework

Research objective	Research Question	Applied methodology	Declaration of authorship	Status publication
RO1: Identify methods that were used to evaluate interactions among SDG entities	RQ1: Which methods were used to evaluate interactions among SDG entities?	Systematic literature review	Publication I (co-author)	Submitted to 'Environmental Science and Policy', 12.08.2021
RO2: Assess the methods with respect to their ability to assess (i) effects between SDG entities, (ii) interdisciplinary sensitivity, (iii) to support collaboration and system thinking and (iv) to their practicability of application	RQ2: How do the methods used for the evaluation of interactions among SDG entities differ?	Expert's assessment using a developed set of evaluation criteria		
RO3: Identify uncertainty issues that occur in decision-making practice using the AHP	RQ3: Which uncertainty issues occur in decision-making practice using AHP?	Critical literature review	Publication II (main author)	Published in 'Journal of Multi-Criteria Decision Analysis', accepted 21.06.2018
RO4: Develop a procedure to consider uncertainty in decision making practice solving sustainability problems and using the AHP	RQ4: How to systematically assess uncertainty referring to a specific decision-making case using the AHP?	Development of a comprehensive uncertainty analysis procedure		
RO5: Assess systematically the quantitative impact of uncertainty issues on the decision-making in the context of sustainable development using the AHP	RQ5: What is the numerical impact of uncertainty on the decision alternatives' priorities for different uncertainty scenarios?	Application of a comprehensive uncertainty analysis procedure embracing a		Published in 'Journal of Multi-Criteria Decision

	RQ6: Does the consideration of uncertainty leads to rank reversals compared to the alternatives' ranking neglecting uncertainty for different uncertainty scenarios?	broad-scale simulation experiment programmed with R		Analysis', accepted 21.06.2018 (continued)
RO6: Develop new analytical methods that allow to prioritize SDG targets	RQ7: How can the ANP be applied to prioritize SDG targets?	Application of the ANP to a country case study	Publication III (main author)	Published in 'Sustainability Science', accepted 12.07.2021
RO7: Understand the ability of different analytical methods to formulate policy advice for coherent SDG implementation	RQ8: How do the different SDG analytical methods differ with respect to their potential to formulate policy advice?	Comparison of analytical methods with respect to their potential to formulate policy advice		
RO8: Analyze if different analytical methods provide varying SDG target rankings referring to a single case	RQ9: Is the SDG target ranking sensitive to the applied analytical method?	Comparison of the SDG target rankings computed by two different analytical methods with respect to a single case		
RO9: Improve the overall quality developed policy advice regarding SDG implementation	RQ10: Does a multi-method application can provide better policy advice compared to a single method application?	Application of a multi-method approach to a country case study		
	RQ11: How can methodological results be translated into applicable policy advice?	Framing methodological results as advice		

The thesis targets the research objectives with three publications:

Publication I: Horvath, S.M. Muhr, M; Kirchner M; Toth W.; Germann V.; Hundscheid L.; Vacik H.; Scherz M; Kreiner H.; Fehr F.; Borgwardt F.; Gühnemann A.; Becsi B.; Schneeberger A.; Gratzer G. (2021) Handling a complex agenda: a review and assessment of methods to analyse SDG entity interactions, Environmental Science and Policy (under review)

Publication II: Toth W, Vacik H (2018) A comprehensive uncertainty analysis of the analytic hierarchy process methodology applied in the context of environmental decision making. J Multi-Criteria Decis Anal 25(5–6):142–161. https://doi.org/10.1002/mcda.1648

Publication III: Toth, W., Vacik, H., Pülzl, H., & Carlsen, H. (2021). Deepening our understanding of which policy advice to expect from prioritizing SDG targets: introducing the Analytic Network Process in a multi-method setting. Sustainability Science, article in press. doi:10.1007/s11625-021-01009-7

In particular, the single research questions are approached by the development and application of two well-known IT-supported MCDM techniques, namely with the AHP and the ANP while considering two different sustainability problems referring one to the micro level perspective (Publication II) and the other one to the macro-level perspective (Publication III). Uncertainty is addressed with the application of two different approaches, embracing firstly a broad-scale sensitivity/uncertainty analysis (Publication II) and secondly the application of multiple models to a single case as part of a multi-method approach (Publication III). Additionally, these analyses are supplemented by two literature reviews, a multi-criteria assessment of reviewed methods analyzing SDG target entity interactions (Publication I) and by framing the methodological results of the SDG target interactions as a typical advice (Publication III).

In Figure 2 a graphical overview of the research activities in the thesis is provided.

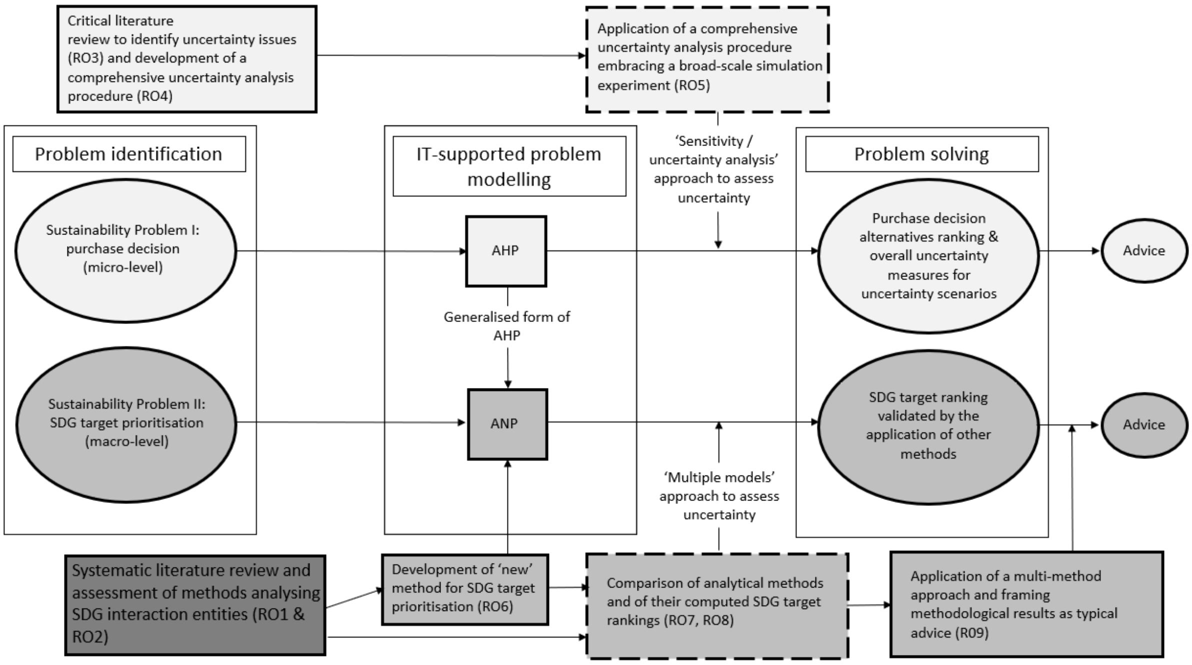


Figure 2: Graphical overview of research framework (Publication I: dark grey elements, Publication II: light grey elements, Publication III: mid grey elements and uncertainty assessment approach: dashed line boxes)

3 Material and methods

3.1 Literature reviews

3.1.1 Systematic literature review

A systematic literature review has been examined as part of Publication I. On 16.12.2019, the literature was extracted from the SCOPUS electronic database via the following search string: 'Sustainable Development Goals' AND 'interlink*' OR 'interact*' OR 'synerg*' OR 'trade-off*' OR 'co-benefit*' OR 'externalit*'. The search was restricted to the date of the establishment of the 2030 Agenda in 2015 and onwards. Furthermore, only scientific literature in English was covered. This resulted in a collection of 1.744 publications, which were screened by the author team regarding their overall relevance considering two steps (see Figure 3).

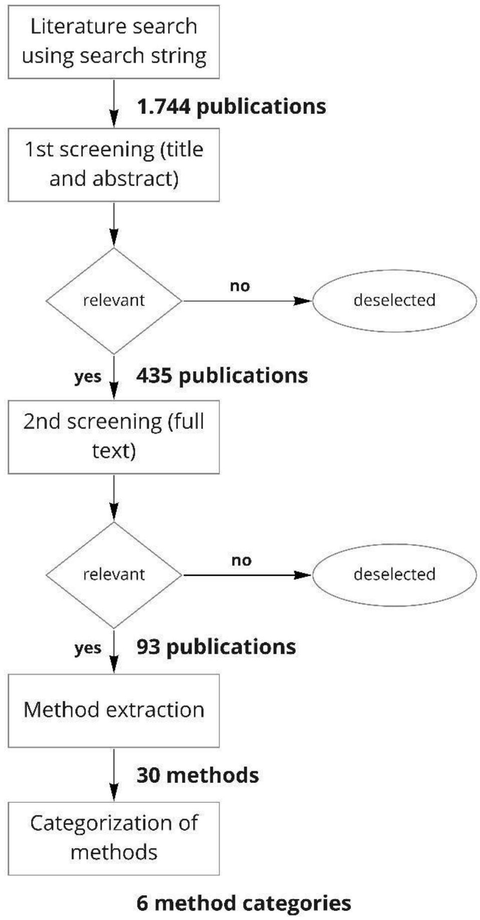


Figure 3: Illustration of the review process steps and retrieved number of publications, methods and categories

The relevance conditions applied are as follows: The publication assesses interactions between at least two SDG entities, i.e., SDGs/targets/indicators/policies or external entities. SDG policies (i.e., policies designed to act towards achieving an SDG, target or indicator) and external entities are only included in the analysis if they are explicitly assigned to an SDG/target/indicator in Publication I. After this refinement, 93 publications were selected for further analysis and categorized by adapting classifications from earlier reviews (Bennich et al., 2020; Miola et al., 2019). From this set of publications, methods that were used to analyze SDG entity interactions were retrieved and allocated to six distinct approach categories (Argumentative, Literature, Linguistic, Simulation, Other quantitative and Statistical). After group discussions of the author team, a consolidated list of thirty methods was compiled (see results in section 4.1). The methods were briefly described in method fact sheets (for exemplary fact sheets, see supplementary materials in section 8.1.1.1), drawing on the publications that they were retrieved from and, in some cases, further literature. In combination with group discussions (sub groups of the author team), these fact sheets were used to gain a common understanding of the methods as basis of their assessment (see section 3.2).

3.1.2 Critical literature review

As a general overview about the uncertainty issues related to the application of the AHP is missing (see section 1.1.5), a critical literature review including scientific as well as grey literature was conducted to identify the most significant uncertainty issues in the field as part of Publication II. The uncertainty issues identified has been categorized according to the four different steps of multi-criteria decision making (Belton & Stewart, 2002) considering group decision making as well (see results in section 4.3).

3.2 Expert's assessment using a developed set of evaluation criteria

As crucial part of Publication I, a set of criteria was developed by the author team (Table 6) to evaluate the methods identified in the systematic literature review (see section 3.1.1). Based on method fact sheets and author team discussions the methods were assessed using this set of evaluation criteria. The criteria are inspired by the set of criteria published by Vacik et al. (2014) and were adapted and extended to the specific collaborative planning context of assessing interactions among SDG entities.

All the criteria were assessed using a binary scale (T=true, F=false), except for criterion 19, which measures the time effort using a scale from 1 (low time effort) to 4 (high time effort). The preference direction for the assessment criteria was harmonized in such a way that fulfilling a criterion ('true') indicates a positive quality in the assessment (e.g., criterion 17 'requires specialized knowledge of methodology' was changed to 'does not require specialized knowledge of methodology').

Each method was assessed by a group of three authors who own expertise regarding the method evaluated. First, each person assessed the method independently. Then, the results of the independent assessments were discussed in the assessment group and a consensus assessment for each criterion was agreed upon. There was one assessment group for each approach category. In some cases, evaluators were members of more than one assessment group, which supported a common understanding of the assessment criteria. It is important to clarify that the assessment was performed at the level of methods, not at the level of publications, considering that one publication can use a combination of more than one method.

Table 6: Criteria for the assessment of methods

	Criterion	Short description	Description
Effects between SDG entities	c1	allows to detect effects	The method allows to show effects from one SDG entity on another
	c2	allows to detect the direction of effects	The method allows to show the direction of an effect from one SDG entity on another
	c3	allows to detect the polarity of effects	The method allows to show whether one SDG entity has a positive (enhancing) or negative (counteracting) effect on another
	c4	allows to detect the degree of effects	The method allows to detect the degree in which a certain SDG entity has an effect on another (e.g., strong, medium, weak effect; range from 1-3)
	c5	allows to detect feedbacks (or feedback loops)	The method allows to detect feedback loops relating to the effects of SDG entities (e.g., reinforcing (+) or balancing (-) feedback loops)

Interdisciplinary sensitivity	c6	allows to include qualitative information	The method allows including qualitative information into the assessment. Qualitative information is understood as the opposite to quantitative information. Thus, qualitative information is information that is not quantified. For the assessment the information/data that finds entrance into the method is considered. If a quantification step is necessary to be able to use the information/data in the method and the quantification step is not part of the method, qualitative data cannot be included into the method and the criterion must be evaluated with 'false (F)'
	c7	allows to include quantitative information	The method allows including quantitative information into the assessment. For the assessment the information/data that finds entrance into the method is considered. If a quantification step is necessary to be able to use the information/data in the method and the quantification step is not part of the method, the data is regarded as qualitative (and the criterion is evaluated with 'false (F)'). If data is used in the method that is already quantified, or if the quantification step is part of the method, these data is regarded as quantitative information
	c8	allows to include implicit knowledge	The method allows taking into account implicit knowledge (indigenous knowledge, local experiences, declarative and procedural knowledge, etc.) in the assessment. Implicit information is here understood in contrast to explicit information which is explicitly declared in documents such as text, pictures, sound, etc. Implicit information also includes expert knowledge which is not documented in models, publications, reports, etc. but is activated during the application of the method. Therefore, implicit information gets transformed into explicit information during the process of method application.

Interdisciplinary sensitivity (continued)	c9	allows to consider individual/ subjective preferences and/or values	The method allows including subjective preferences and/or values in the assessment (individual or collective from a group). These preferences are not directly based on objective information, such as empirical data, statistical information and other scientific evidence, but on experiences, traditions, religious or cultural aspects, and value judgements. These preferences can be expressed for example as: • for the priority of targets or SDGs in the assessment • for the importance of the multiple effects of interactions between SDG entities • for the importance of individual policies (in the case of a mix of policies to reach a target) • for the overall assessment of policies with regard to evaluation criteria (costs, effectiveness, efficiency, etc.)
Collaboration and systems thinking	c10	allows information about the certainty of results	The method allows indicating information about the degree of certainty/uncertainty involved in the evaluation of the effects/interactions (e.g., value for uncertainty in statistical calculations, expert judgements, etc.)
	c11	operates transparently	The method operates in a transparent way. The underlying mechanisms/calculations are comprehensible and clear
	c12	produces results that are easy to interpret	The method produces easy to handle results or information (e.g., illustrative results such as graphs, tables, figures or descriptive texts). The interpretation of results does not require specialized knowledge by the most probable end users

Practicability of application	c13	can be adapted to different scales	The method can be adjusted to different spatial and temporal scales of application (spatial: global, regional, local; temporal: past, present, future effects/interactions).
	c14	can be used in a collaborative setting	The method can be used collaboratively. The collaboration is part of the method application process. The method facilitates and supports communication and interaction among the people involved and creates a collaborative atmosphere
	c15	allows to be applied in a big group (>10 people)	The method can be applied in a large group (10 or more people) and thus integrate a large number of experts into the assessment
	c16	increases system understanding of involved experts	The method increases the understanding (e.g., of the process itself, of the information processed) of the subject for the experts involved in the assessment. The process aligned with the method application increases the system understanding of the involved experts. (Not included: the increased system understanding that is caused by the results of the method)
	c17	does not require specialized knowledge of methodology	The person/people conducting the assessment does/do not need specialized methodological knowledge to perform the assessment
	c18	does not require computer-based support	The method does not necessarily require computer-based support (e.g., special software, hardware) to be applied
	c19	time effort needed	The amount of time needed to apply the method is assessed from the applicant's researcher's perspective. The time effort is to be assessed relative to all other methods in the assessment. It is assumed that the necessary expertise for applying the method is already in place and that e.g., a model or a statistical method already exists.

3.3 Development and application of a comprehensive uncertainty analysis procedure

A comprehensive uncertainty analysis procedure has been developed as part of Publication II. The procedure allows the analysis of the involved uncertainty regarding a specific sustainability problem embracing the designation, the categorization and the quantification of uncertainty. The sequence of the eight detailed steps is shown in Figure 4 and related to the application of the AHP.

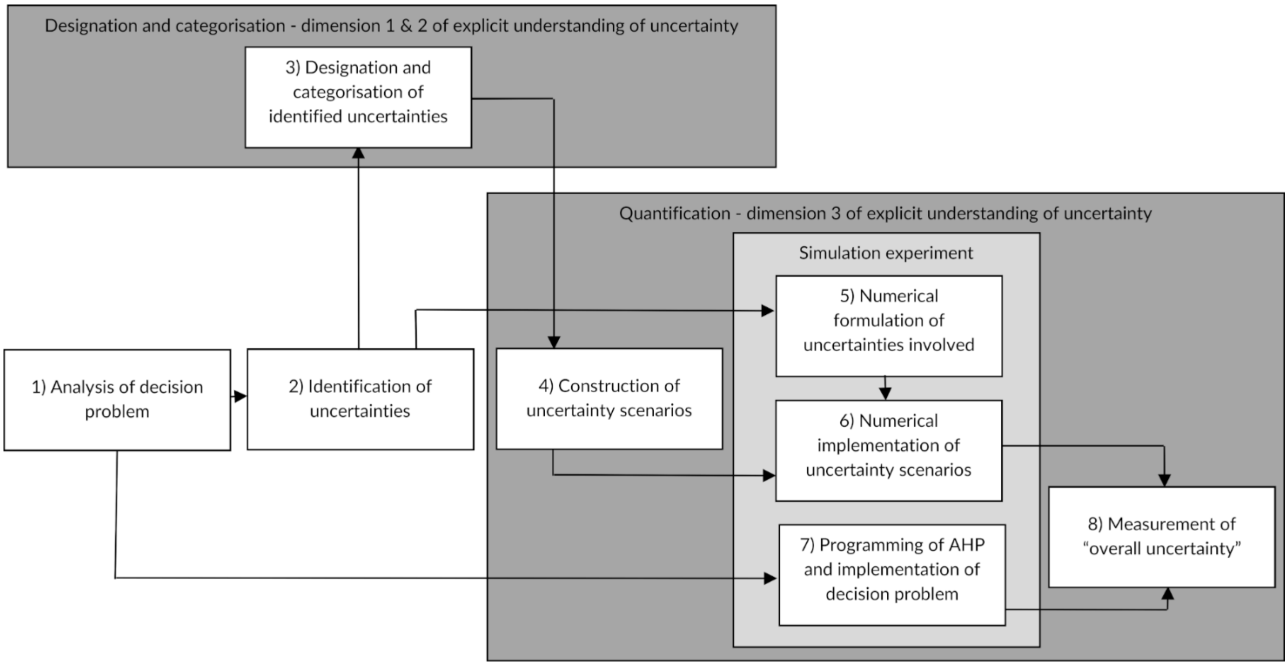


Figure 4: Procedure of a comprehensive uncertainty analysis

1) The procedure starts with the elaboration of an in-depth analysis of the sustainability problem. This is done by building the decision hierarchy used in the AHP, collecting available input data and its embedded assumptions and clarifying the system boundaries to be modelled. Additionally, the fundamental characteristics of the decision problem are elaborated in the sense of common properties in a specific context. Such common properties of sustainability problems are for example

i) 'ill-defined' as there are various and competing stakeholders' narratives and framings of what is the problem to solve
ii) extended temporal and spatial scales of impacts in environmental systems (see section 1.1.2).

This helps to reveal the linkages of the decision problem with the uncertainty causing methodological properties of the AHP as shown in the overview of uncertainties associated with the AHP in section 4.3.

2) Based on this in-depth analysis, uncertainties involved can be identified. The relevance and kind of uncertainties may vary among different application areas like sustainability decision making or technical engineering.

3) Subsequently, the identified uncertainties are designated and classified with respect to the provided categories (see Publication II in section 8.2).

4) The quantification of uncertainty involves the construction of uncertainty scenarios (USs) that capture all possible combinations of the identified uncertainties.

5) Based on literature research and/or expert judgements, a numerical formulation of these uncertainties should be established.

6) For completion of the quantification, a simulation experiment is conducted. It includes programming of the AHP accompanied by the implementation of the decision problem.

7) Furthermore, the simulation experiment embraces a numerical implementation of the constructed USs.

8) The synthesis allows to measure 'overall uncertainty', i.e., to test the numerical impact of the identified uncertainties on the final alternative ranking involved in the decision problem under consideration.

3.3.1 Sustainability problem I – Purchase decision (Micro-level)

The first sustainability problem is concerned with a hypothetical purchase decision of a single household relating to the micro-level perspective. It is about making a choice regarding a new a heating system for a family house located in Vienna, Austria. The family embraces the parents (father and mother) and two children (adolescents) mutually deciding on this purchase problem involving all three dimensions of SD. Guidelines and information material usually present a broad range of possible heating system alternatives (Cerveny & Sturm, 2012; Federal Environment Agency, 2001). After consulting guidelines provided by local authorities (Huber, Schöfmann, & Zottl, 2014) it becomes clear that due to the specificity of the piece of ground any heating-system using terrestrial heat is not compatible with current law. Also, combinations of different technologies are technically possible, but neglected here. Furthermore, it is decided to neglect any coal heating-system, because of its massive environmental impact. As a result, the alternatives Logs, Wood pellets, Natural Gas and Oil are considered in the purchase decision. For evaluating the heating system alternatives, the set of criteria Costs, CO_2-emissions, Feeling of security and Security of resource supply. The decision problem is framed as a three-level hierarchy and thus can be utilized as model input for the AHP (see Figure 5).

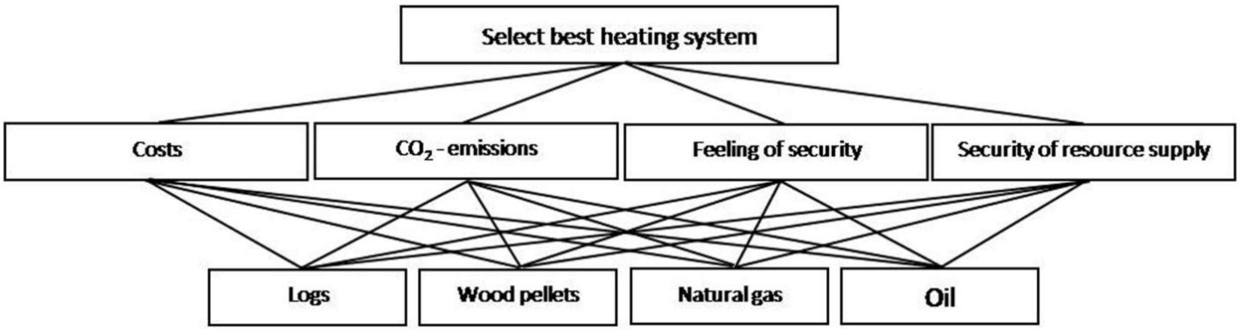


Figure 5: Hierarchical representation of purchase decision problem

Two of the included criteria (Costs and CO_2 - emissions) are a matter of gathering quantified data and the other two (Feeling of security and Security of resource supply) are a matter of qualitative evaluation (see Table 7).

3.3.2 Simulation experiment - Conceptual description

The quantification part of the procedure of a comprehensive uncertainty analysis has been conducted by programming a simulation experiment using R (R Development Core Team, 2014). The simulation experiment roughly embraces three steps: 1) the programming of the original AHP, its validation against literature examples and the provision of input data, 2) simulating three variants of different group preferences and 3) the inclusion of uncertainties using several USs including different combinations of single uncertainties. The basic idea behind this simulation experiment is to check the quantitative impact of uncertainties on the AHP model result.

3.3.2.1 Programming the original AHP

After programming the original AHP and its validation against literature examples, data can be included into the model. The input data used relates to the purchasing decision of a new heating system is shown in Table 7. The alternatives' performance under the criterion Costs represents life cycle costs. The data is related to an assumed heating energy consumption of 30,000 kWh per year (corresponds to a living area of about 180 m2 (E-Control, 2004)) and to an assumed constant average price level for different energy sources for 20 years (Cerveny & Sturm, 2012). The alternatives' performance under the criterion CO_2 - emissions also embed a life cycle view and includes the emissions produced throughout the life cycle of a specific energy source (Federal Environment Agency, 2001).

Table 7: Performance of alternatives with respect to the criteria

Alternatives	Criterion			
	Costs [EUR]	CO_2-emissions [kg / 1 kWh useful energy]	Feeling of security	Security of resource supply
Logs	3004	0.07	Qualitative evaluation	Qualitative evaluation
Wood pellets	3666	0.06		
Natural gas	3772	0.26		
Oil	4547	0.39		

The alternatives' performance under the criterion Feeling of security and Security of resource supply is a matter of qualitative evaluation. Feeling of security refers to eventual carbon-monoxide emissions from a boiler or complications in a fireproof wood pellet heating room. Security of resource supply for example has to do with the perception of frictions between Russia and Ukraine and the related natural gas dependency of Austria. The qualitative evaluation was examined by the determining a preference tendency (PT), which is a specific relative importance ranking (Butler, Jia, & Dyer, 1997) (e.g., A is more preferred than B, but it is not determined how much more, then A is ranked as 1 and B as 2).

3.3.2.2 Simulating three variants of group preferences

As the purchase of the heating system is simulated as group decision, several PTs have to be determined for each family member. Additionally, three variants of different group preferences (and hence with different PTs) are computed considering the three stories

a. specific stereotypes (variant I)
b. equal preferences of group members (variant II) and
c. maximal diverging group preferences (variant III).

An exemplary determination of PTs with respect to the evaluation of the relative importance of the used criteria is shown in Table 8, whereas all determined PTs are documented in detail in Publication II in the appendix.

Table 8: Exemplary PT of family members: Relative importance ranking with respect to the criteria

	Family member	Criteria: Costs	Criteria: CO_2 - emissions	Criteria: Feeling of Security	Criteria: Security of resource supply
Variant I	Father	1	3	4	2
	Mother	3	2	1	4
	Child 1	3	1	2	4
	Child 2	4	1	2	3
Variant II	Father	1	2	3	4
	Mother	1	2	3	4
	Child 1	1	2	3	4
	Child 2	1	2	3	4
Variant III	Father	1	2	3	4
	Mother	2	4	1	3
	Child 1	3	1	4	2
	Child 2	4	3	2	1

Based on these PTs, the input data for the qualitative evaluation of the alternatives' performance regarding the criteria (see Table 7) can be derived. This was done by producing randomized data, in particular random pairwise comparison matrices. For conducting simulation experiments with respect to the AHP methodology, different authors used various amounts of random pairwise comparison matrices. The maximal amount of a few millions was used by Aull-Hyde, Erdogan & Duke (2006) or Herman & Koczkodaj (1996). Based on that experience, a pool of 3*10^6 random pairwise comparison matrices is considered as sufficient. The random pairwise comparison matrices included in this pool undergo a consistency check and a match with the PT involved to be further used as input data for the total simulation runs.

3.3.2.3 Inclusion of uncertainty scenarios

Four single uncertainties were identified with respect to the specifics of the heating system purchase problem taken into account its wicked characteristics.

3.3.2.3.1 Model conceptualization uncertainty

SD has to cope with potential impacts in natural systems that occur in extended temporal and spatial scales (Dovers, 2005). For example, the extraction of oil (demanded by oil heating-systems) may lead to natural disasters, such as the consequences from the Deepwater Horizon oil spill. Such low-probability, high-impact events are hard to assess and thus it is a challenge to find a reasonable integration into problem modelling. In particular, for decision-makers who are not decision-making specialists (e.g., a family) such impacts may be only suspected, but not explicitly articulated. Hence, the model conceptualization uncertainty associated with the incorporation of important, but ‘unknown’ factors’ is considered.

Uncertainty associated with the development of the model structure is inherently related to the formulation of the decision problem hierarchy (Belton & Stewart, 2002; Maier, Ascough, Wattenbach, Renschler, & Labiosa, 2008). There are no rules which hierarchical representation is most suitable to a specific decision-making problem. Different analysts show varying problem perceptions and thus come up with different decision models (J.C. Refsgaard, Van der Sluijs, Højberg, & Vanrolleghem, 2005). Brugha (1998; 2004) offers methodological suggestions how to elaborate structured criteria trees. Also, Wedley (1990) provides guidelines what to include in hierarchies. Saaty and Begicevic (2010) propose general lists of human values and activities to support problem structuring, i.e., to ensure the inclusion of all important elements. Nevertheless, if a model is set up, questions like ‘are all relevant factors considered?’ or ‘are there relevant criteria remaining that are suspected, but cannot explicitly articulated?’ may arise (Ozdemir & Saaty, 2006). If there is awareness that there are other important criteria covering some ‘unknown’ factors, a way to integrate them into the problem formulation has to be identified. Ozdemir and Saaty (2006) propose the implementation of another criterion, called 'other' into the AHP-model to check whether the best alternative is sensitive to hidden factors. The criterion 'other' is introduced as additional criteria into the model. It expresses the confidence about covering all relevant aspects regarding the decision problem.

3.3.2.3.2 Incomplete pairwise comparison matrix uncertainty

This perceived inscrutability of dependencies likely leads to situations that cause missing elements in the assessment process. For example, the two children have to evaluate the involved alternatives under the criterion Security of resource supply. They might not be able to accurately judge, because the pairwise comparison of the alternatives requires knowledge (e.g., knowledge about international energy politics as a consequence of Russian's foreign affairs) that children usually do not have. Hence, 'uncertainty associated with incomplete pairwise comparison matrices' is incorporated as second uncertainty in the analysis.

Dittrich et al. (2012) identifies six different situations that can cause missing elements in a pairwise comparison matrix, of which one is relevant for here: Respondents may fail to respond, because of their insufficient knowledge to judge. Deparis et al. (2012) empirically investigates the expression of incomplete preferences linked to multi-criteria comparisons and reports that evaluating procedures that do not design the inclusion of incomplete preferences may lead to the expression of an indifference response instead of an incomplete expression. Incomplete pairwise comparison matrices may appear with a differing number of missing elements. Hence, to tackle one of these cases several procedures (e.g., transitivity rules or applying consistency optimization and simulation techniques) are provided in literature (Bozóki, Fülöp, & Rónyai, 2010; Kwiesielewicz & Van Uden, 2003). The chosen method of calculating the missing data implicitly embeds a specific intention with respect to the decision makers, hence at the beginning of the recalculation it is necessary to clarify these intentions and then to choose the most suitable method (Kwiesielewicz & Van Uden, 2003). Humans understand the meaning of words better and hence prefer to use verbal expressions. They are intuitively appealing and more common in our everyday lives than numbers (Huizingh & Vrolijk, 1997; Ishizaka & Labib, 2011a). To tackle this human characteristic, the first-level transitivity rule proposed by Srdjevic et al. (2014) is choosen, because it only uses values from the Saaty-scale to recalculate missing elements. These values correspond to exact semantic statements, which can be used for communication and queries with the involved decision makers (Saaty, 1995).

3.3.2.3.3 Aggregation mode uncertainty

The original AHP relies on additive aggregation of criteria priorities and local alternative priorities to a final alternative ranking (Saaty, 1999a). Criticism of this procedure has been formulated by several authors and a multiplicative aggregation has been proposed. The referring debate is in depth summarized by Ishizaka and Labib (2011a). However, simulation experiments show differences between the usages of these two aggregation modes (Stam & Duarte Silva, 2003), therefore the 'uncertainty associated with the aggregation mode between the different levels of the problem modelling hierarchy' is considered as relevant, because of its long-lasting and fundamental debate. Conceptually, the integration is done by replacing the additive aggregation of the local alternative priorities by a multiplicative aggregation.

3.3.2.3.4 Group aggregation method uncertainty

Solving sustainability problems in a sustainable way requires the involvement of relevant stakeholders. It is likely that this 'community participation' enhances the acceptance of the decision outcome (Dovers, 2005; Harding, Hendriks, & Faruqi, 2009). Hence, also the children are included in making the decision. Therefore the 'uncertainty associated with the combination procedure of several decision makers' judgments' is seen as important for this case. Therefore, the opinions of the family members have to be merged into one group decision. Given such individual judgements, several ways of aggregating them to a group decision exist. Mikhailov (2004b) presents a group fuzzy preference programming method, a Bayesian approach is developed by Altuzarra et al. (2007) and also procedures linking consistency considerations to a consensus view are proposed (Dong, Zhang, Hong, & Xu, 2010; Moreno-Jiménez, Aguarón, & Escobar, 2008). Additionally, Grošelj et al. (2015) compare seven simple aggregation procedures numerically and developed measures to evaluate them. Ishizaka and Labib (2011b) summarize that there are four ways to integrate the involved decision-makers' preferences into a consensus rating, two of them are mathematical procedures. Also, Grošelj et al. (2015) identify a geometric mean on the judgements in the pairwise comparison matrices and a weighted arithmetic mean on the derived criteria and local alternative priorities as the two main mathematical aggregation algorithms. Researchers have some disagreement on the use of individual judgments in pairwise comparison matrices or for deriving criteria and local alternative priorities in a group choice (Srdjevic & Srdjevic, 2013). Criticism was formulated because the application of the geometric mean method may violate the pareto optimality (if all group members prefer A, then a group outcome A should also be preferred, compare (Ramanathan & Ganesh, 1994) and the aggregation of criteria and local alternative priorities may violate Arrow's Impossibility Axioms (Saaty & Vargas, 2012). Forman and Peniwati (1998) argue that the perception of the group (as a synergistic unit or as a collection of individuals) determines the aggregation method to use. However, both options are included into the simulation experiment. These four uncertainties are combined into 14 USs including different combinations of the single uncertainties (see Table 9).

Table 9: Overview uncertainty scenarios and original versions of AHP

	Uncertainties			
Uncertainty scenarios (US) and two versions of original AHP	Model conceptualization	Incomplete pairwise comparison matrix	Aggregation mode	Group aggregation method
Original AHP_wam	✗	✗	✗	Weighted arithmetic mean (wam)
US1_wam	✓	✗	✗	wam
US2_wam	✗	✓	✗	wam
US3_wam	✗	✗	✓	wam
US4_wam	✓	✓	✓	wam
US5_wam	✓	✓	✗	wam
US6_wam	✓	✗	✓	wam
US7_wam	✗	✓	✓	wam
Original AHP_gm	✗	✗	✗	Geometric mean (gm)
US1_gm	✓	✗	✗	gm
US2_gm	✗	✓	✗	gm
US3_gm	✗	✗	✓	gm
US4_gm	✓	✓	✓	gm
US5_gm	✓	✓	✗	gm
US6_gm	✓	✗	✓	gm
US7_gm	✗	✓	✓	gm

3.3.2.4 Computation of overall uncertainty measure

As the basic idea behind checking the quantitative impact of uncertainties on the AHP model result is a sensitivity analysis (see Table 4), an overall uncertainty measure has been accounted for the total simulation runs. The computation of the different USs allows formulating a simple and intuitively understandable quantitative measure that may be interpreted as 'overall uncertainty'. With respect to the total simulation runs, the 'overall uncertainty' measure is expressed as percentages that indicate if and how often the inclusion of a specific US changes the rank of the best alternative given by the original AHP without considering any uncertainties, i.e., in % rank reversal.

3.3.3 Simulation experiment - Mathematical description

As the aim is here to only present the conceptual part of the simulation experiment, a detailed and in-depth mathematical description of the simulation experiment including a flow-chart of the algorithms, defined sets, and a documentation how the uncertainties are programmed is provided in Publication II in the appendix.

3.4 Application of the ANP presented with a hypothetical example

Publication III demonstrates how to apply the ANP to prioritize SDG targets. To ensure that the description of the methodological approach is also readily perceivable for any reader who is not a specialist in this particular field of multi-criteria analysis techniques, a hypothetical SDG target network serves as a simplified demonstration of the process. The hypothetical SDG target network consists of two SDGs (SDG 1 and SDG 15) and three SDG targets each which is shown in Figure 6.

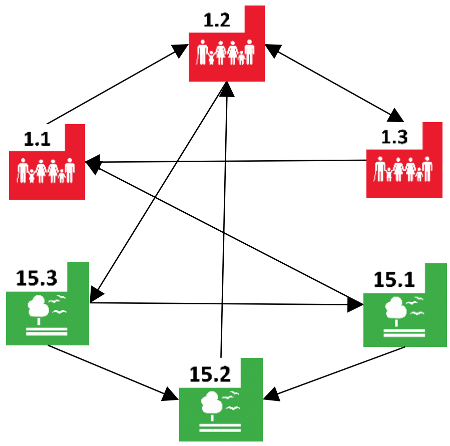


Figure 6: Network representation of SDG targets prioritisation problem

The arrows indicate the direction of influence between SDG targets and whether there is a uni-directional (SDG target 1.3 influences SDG target 1.5) or a bi-directional interaction (SDG target 1.2 and SDG target 1.3 influence each other) between two SDG targets. The methodological description follows the best practice checklist for ANP reporting (Mu, Cooper, & Peasley, 2020). Hence, the reader is guided through the development of the SDG target network model and the subsequent computations of the SDG target rankings. The application was performed using the free software product Super Decisions v.3.2.0 (SuperDecisions, 2019a).

3.4.1 Model development, evaluation question and rating scales

The SDG targets serve as nodes in the ANP model and are contained in one inner-dependent cluster, meaning that all of the cluster's nodes only depend on elements of this cluster. For the SDG targets (nodes) that show an interaction, links were established within the model to allow the integration of the respective SDG target interaction data. With respect to the hypothetical example, the SDG target network consists of six SDG targets (see ANP model in Figure 7).

The common AHP/ANP application and its measurement procedure rely on data input that originates from a pairwise comparison of system elements using a pairwise-comparison matrix. In the hypothetical example, this would mean comparing the interaction of two SDG targets with respect to another single SDG target. As shown in the pairwise-comparison matrix concerning SDG target 1.1 in Figure 7 a), SDG target 15.1 demonstrates an interaction with SDG target 1.1 that is 1.5 times larger than the interaction of SDG target 1.3 with SDG target 1.1. Qualitatively and using the Saaty-scale, the interaction of SDG target 15.1 with SDG target 1.1 is 'equally to moderately more' larger than the interaction of SDG target 1.3 with SDG target 1.1 (Saaty & Vargas, 2013). Conducting such a pairwise-comparison of all the system elements with respect to each other for each SDG target would lead to six pairwise-comparison matrices, concerning the single SDG targets 1.1, 1.2, 1.3., 15.1, 15.2 and 15.3. This is shown with two exemplary matrices in Figure 7 a). Pairwise-comparisons allow consideration of the otherwise intangible (unmeasurable) relationship between two elements in the ANP. Based on the pairwise comparisons matrices, priority vectors can be calculated that include the relative 'importance' of the elements with respect to the single element they are compared to. These normalized priority vectors would then be collected in the unweighted supermatrix for further calculations (Saaty & Vargas, 2013) (Figure 7 a)).

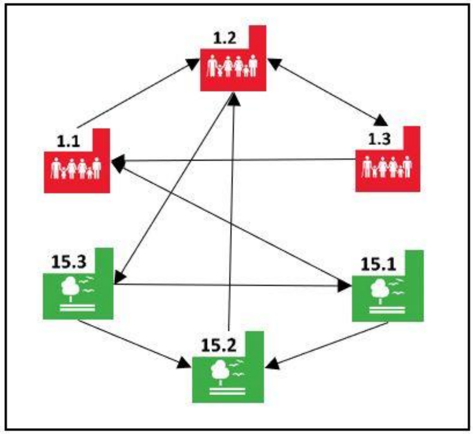
However, the elicitation of the input data used for the application of the ANP to the case study follows a different procedure. The data is gathered using the Nilsson-scale asking the question 'If progress is made on target x (rows), how does this influence progress on target y (columns)?'. As the underlying mathematics of the ANP relies only on positive values, only the positive interaction scores can be used in this application. Two models were built, considering 1) the influence from a single SDG target on all other SDG targets and 2) from the perspective of a single SDG target, the influence received from all other SDG targets. For demonstration purposes, and with respect to the hypothetical SDG target network, only the model considering the influence from a single SDG target on all other SDG targets is presented (Figure 7 b)).

All SDG interaction scores are then collected in a cross-impact matrix (CI-matrix) which shows the network under consideration and contains all the elements listed horizontally and vertically (Weitz et al. 2018). Hence, the CI-matrix is identical to the initial supermatrix of the ANP (Saaty & Vargas, 2013). The referring quantitative scores were subsequently put into the ANP model using the direct data entry mode in Super Decisions v.3.2.0 instead of the common pairwise comparisons and were therefore collected in the initial supermatrix ((Figure 7 b)) (Adams & Saaty, 1999) to derive the unweighted supermatrix.

3.4.2 Consistency

The consistency check is an essential process step and usually applied as instrument to prove if two corresponding scores in the initial supermatrix (e.g., SDG target 1.3 directly influences SDG target 1.5 and SDG target 1.5 directly influences SDG target 1.3) are logical in terms of the goodness or ‘harmony’ in the context of the total network (Bozóki & Rapcsák, 2008). However, as the data was entered directly into the model and as no pairwise comparisons were used, there was no need for the consistency check in this research. Nevertheless, the scores do not need to be consistent or even transitive to be further computed using the ANP (Saaty, 1990).

ANP model



a)

Pairwise comparison matrix with respect to SDG target 1.1

	1.3	15.1
1.3	1	0.667
15.1	1.5	1

→ $\begin{pmatrix}0.4\\0.6\end{pmatrix}$

Pairwise comparison matrix with respect to SDG target 1.2

	1.1	1.3	15.2
1.1	1	0.5	0.5
1.3	2	1	1
15.2	2	1	1

→ $\begin{pmatrix}0.2\\0.4\\0.4\end{pmatrix}$

Unweighted supermatrix

SDG targets	1.1	1.2	1.3	15.1	15.2	15.3
1.1	0.000000	0.200000	0.000000	0.000000	0.000000	0.000000
1.2	0.000000	0.000000	1.000000	0.000000	0.000000	1.000000
1.3	0.400000	0.400000	0.000000	0.000000	0.000000	0.000000
15.1	0.600000	0.000000	0.000000	0.000000	0.666667	0.000000
15.2	0.000000	0.400000	0.000000	1.000000	0.000000	0.000000
15.3	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000

b)

Cross-impact matrix = initial supermatrix

	1.1	1.2	1.3	15.1	15.2	15.3
1.1	-	1	0	0	0	0
1.2	0	-	2	0	0	3
1.3	2	2	-	0	0	0
15.1	3	0	0	-	2	0
15.2	0	2	0	0	-	0
15.3	0	0	0	1	1	-

Normalisation

Figure 7: Hypothetical example: ANP model development and data input. a) Data input for the ANP using pairwise comparison matrices b) Data input for the ANP using Nilsson scores of the CI-matrix as direct data

3.4.3 Reporting the unweighted and weighted supermatrix

To elicit the priorities given in the scored SDG target interactions which were collected in the initial supermatrix, the local priorities (intermediate step to calculate the final priorities) for each SDG target are calculated by normalizing their referring columns of the initial supermatrix, i.e., by calculating the relative influence of the SDG targets that summed up to 1 (see figure 1 b)). In other words, only the influence with respect to the direct SDG targets' neighbors is considered in this step (1st order influence). For the columns including only one interaction (SDG target 1.3, SDG target 15.1 and SDG target 15.3), the normalization procedure leads to the inclusion of these single SDG target with the relative influence of 1, regardless of their differences in the original score.

The unweighted supermatrix is accordingly composed of these normalized local priorities of all single SDG targets (Saaty & Vargas, 2013; SuperDecisions, 2019b). As there is only one cluster used for modelling the SDG target network, no further calculations using weights for different clusters are needed as the unweighted and weighted supermatrices are identical (see supplementary material in section 8.3.1.1). For the hypothetical example, the weighted supermatrix is presented in Table 10.

Table 10: Hypothetical example: Weighted supermatrix

SDG targets						
	1.1	1.2	1.3	15.1	15.2	15.3
1.1	0.000000	0.200000	0.000000	0.000000	0.000000	0.000000
1.2	0.000000	0.000000	1.000000	0.000000	0.000000	1.000000
1.3	0.400000	0.400000	0.000000	0.000000	0.000000	0.000000
15.1	0.600000	0.000000	0.000000	0.000000	0.666667	0.000000
15.2	0.000000	0.400000	0.000000	1.000000	0.000000	0.000000
15.3	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000

To ensure that the weighted supermatrix is valid to calculate the limit supermatrix (final step to calculate SDG target rankings), the convergence of the weighted supermatrix with respect to the proposed heuristic of Mu et al. (2020) using R (R Development Core Team, 2014) is tested. This means, that it is first checked to see if absorbing nodes exist in the network, indicating that a single node receives influence while not influencing other nodes. Additionally, confirmation is made that the columns of the weighted supermatrix are column-stochastic and therefore composed of normalized priority vectors. Absorbing nodes, as well as a non-column-stochastic weighted supermatrix, leads to a limit supermatrix primarily composed of zeros. Secondly, the weighted supermatrix is checked to see if sufficient links among the nodes are given to prevent the weighted supermatrix fragmenting into smaller subnetworks when calculating the limit supermatrix (Mu et al., 2020). The test result shows that the weighted supermatrix of the hypothetical example is suitable for the task at hand.

3.4.4 Computation of the limit supermatrix (SDG target ranking)

Theoretically, considering all indirect SDG target interactions for any case requires a self-multiplication sequence of weighted supermatrices W that tends to cycle to infinity: the weighted supermatrix itself, its square, its cube, etc., denoted by W^k where $k = 1, 2, \ldots, \infty$. However, to consider all possible indirect SDG target interactions for a specific case involves a search for the limit of that particular sequence. Therefore, the primary goal is to obtain the limit supermatrix by raising the weighted supermatrix to powers by multiplying it times itself till the limit of $W^{n+1} = W^n$ is reached, indicating that the next powers do not add any detail to the result. For the weighted supermatrix, including a cyclic graph, to be relevant for the indivisibly connected SDG target networks, the average influence along all possible indirect SDG target interactions up to a given length is provided by the Cesaro sum $\lim_{k\to\infty} \frac{1}{N}\sum_{k=1}^{N} W^k$, where N is the limit of the sequence of the weighted supermatrices raised to powers (Rokou, Kirytopoulos, & Voulgaridou, 2012; Saaty, 1999b; Saaty & Vargas, 2013; Sava, Vargas, May, & Dolan, 2020; SuperDecisions, 2019b).

When all the columns are identical, the limit supermatrix is converged into a stable matrix and the self-multiplication of the weighted supermatrix is halted. Hence, the limit supermatrix contains the SDG target ranking as the final priorities in each column (see supplementary material). The rationale behind raising the weighted supermatrix to powers is to allow the SDG target network to be represented as a graph in the ANP and permit all direct and indirect SDG target interactions to be considered. Each transition within the network from one SDG target to the next is represented by the corresponding power of the weighted supermatrix. In other words, the power of the weighted supermatrix corresponds to the orders of influence considered within the SDG target network. As the limit N of the sequence of the weighted supermatrices raised to powers is not returned by Super Decisions v.3.2.0, this is called the n-order influence. This is captured by the corresponding sequence of weighted supermatrices W^k where $k = N$. With respect to the hypothetical example, the process of raising the weighted supermatrix to powers is conceptually shown with the systemic understanding of the SDG target interactions in Figure 8. The 1st order influence refers to the sequence of weighted supermatrices W^k where $k = 1$, the 2nd order influence refers to W^k where $k = 2$, the 3rd order influence refers to W^k where $k = 3$ and finally for the n-order influence W^k where $k = N$.

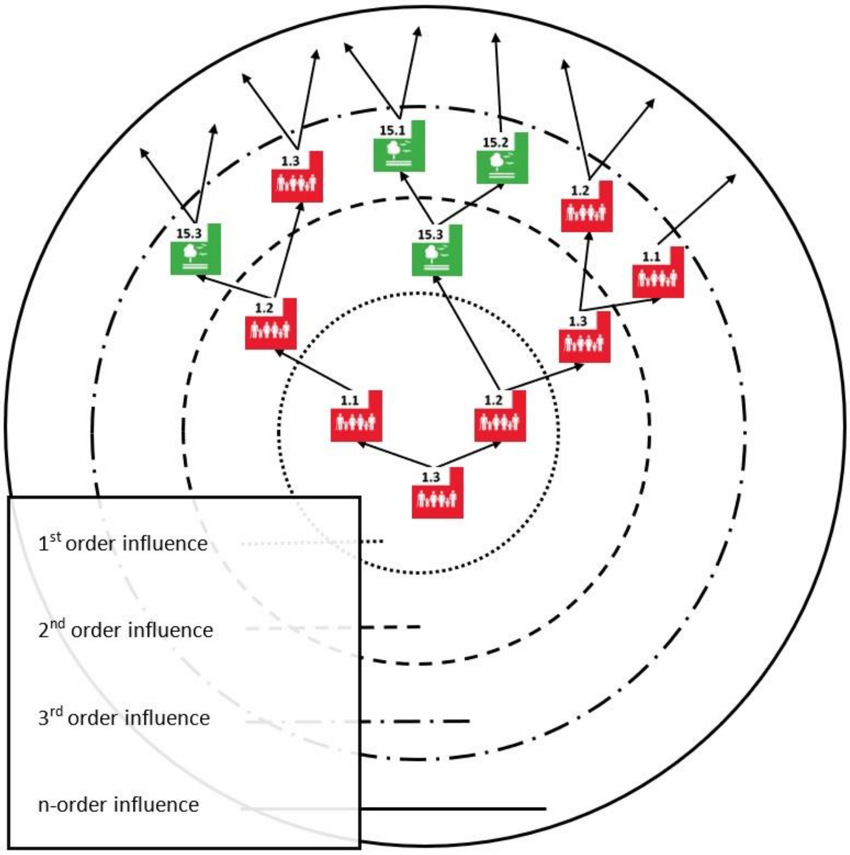


Figure 8: Hypothetical example: A systemic understanding of SDG target interactions. Credit (SDG icons): United Nations.

The columns of the limit supermatrix then establish the final priorities for the SDG targets. With respect to the hypothetical example, SDG target 15.2 is ranked best due to its highest influence on all other SDG targets in the network (Table 11), while considering the 1st order influence, SDG target 1.2 and 15.1 are ranked best (see largest row sum in the CI-matrix in Figure 7 b)).

Table 11: Hypothetical example: Limit supermatrix

SDG targets						
	1.1	1.2	1.3	15.1	15.2	15.3
1.1	0.040650	0.040650	0.040650	0.040650	0.040650	0.040650
1.2	0.203252	0.203252	0.203252	0.203252	0.203252	0.203252
1.3	0.097561	0.097561	0.097561	0.097561	0.097561	0.097561
15.1	0.235772	0.235772	0.235772	0.235772	0.235772	0.235772
15.2	0.317073	0.317073	0.317073	0.317073	0.317073	0.317073
15.3	0.105691	0.105691	0.105691	0.105691	0.105691	0.105691

3.4.5 Sensitivity Analysis

As only the ANP mathematics is used to calculate SDG target rankings, no decision alternatives and criteria are included in the ANP model and hence no sensitivity analysis can be performed regarding the effect on the prioritization of alternatives.

3.5 Multi-method application

Publication III applies the ANP in the context of a multi-method setting to a country case, which is presented in the following section 3.5.1. For conducting the multiple-models uncertainty assessment approach (Table 4) it is necessary to develop a deeper understanding of the analytical methods' potential to formulate policy advice (see section 3.5.2) as a basis to choose the different models for re-calculation (see section 3.5.3).

3.5.1 Sustainability problem II - SDG target prioritization (Macro-level)

The second sustainability problem refers to a macro-level view and analyses the SDG target prioritization for a single country. The country case is taken from Weitz et al. (2018). The authors report that Sweden was selected as the case study because of good data availability and chances to verify the results with the relevant stakeholders. The analysis was done at the level of SDG targets and two targets per goal were selected, i.e., a total of 34 targets. The selection was based on a consideration of what are the most relevant and salient targets for each SDG in the context of Sweden and excluding the 'means of implementation-targets' (Weitz, Persson, Nilsson, & Tenggren, 2015) (see Table 12).

Table 12: Selected 34 SDG targets for the country case of Sweden

SDG target	Official description
1.3	Implement nationally appropriate social protection systems and measures for all, including floors, and by 2030 achieve substantial coverage of the poor and the vulnerable
1.5	By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters
2.2	By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons
2.4	By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality
3.4	By 2030, reduce by one-third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being
3.8	Achieve universal health coverage, including financial risk protection, access to quality essential health-care services and access to safe, effective, quality and affordable essential medicines and vaccines for all
4.1	By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes
4.4	By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship
5.4	Recognize and value unpaid care and domestic work through the provision of public services, infrastructure and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate
5.5	Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life
6.5	By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
6.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
7.2	By 2030, increase substantially the share of renewable energy in the global energy mix
7.3	By 2030, double the global rate of improvement in energy efficiency
8.4	Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year

	framework of programmes on sustainable consumption and production, with developed countries taking the lead
8.5	By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value
9.4	By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities
9.5	Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending
10.1	By 2030, progressively achieve and sustain income growth of the bottom 40% of the population at a rate higher than the national average
10.7	Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies
11.1	By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums
11.2	By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons
12.1	Implement the 10-year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries
12.5	By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse
13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries
13.2	Integrate climate change measures into national policies, strategies and planning
14.1	By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution
14.4	By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics
15.2	By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally

15.5	Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species
16.4	By 2030, significantly reduce illicit financial and arms flows, strengthen the recovery and return of stolen assets and combat all forms of organized crime
16.6	Develop effective, accountable and transparent institutions at all levels
17.11	Significantly increase the exports of developing countries, in particular with a view to doubling the least developed countries' share of global exports by 2020
17.13	Enhance global macroeconomic stability, including through policy coordination and policy coherence

3.5.2 Analytical methods' potential to formulate policy advice

An in-depth understanding of the analytical methods' potential to formulate policy advice means to clarify which methodological result (e.g., an SDG target ranking or a network visualization) can be produced by the single methods. This allows to choose methods that can be used for the multiple model uncertainty assessment approach. Furthermore, knowing the analytical methods' potential to formulate policy advice supports the directed development of practice relevant knowledge for policy making. In particular, it allows to determine which policy challenges (Bennich et al., 2020) the policy advice responds to. With respect to the presented multi-method approach, the analytical methods CI-matrix, the supermatrix of the ANP as well as network analysis are compared, from which the CI-matrix method and the ANP supermatrix are chosen for the multiple model uncertainty assessment.

3.5.3 Re-calculation of SDG target rankings

For applying the ANP in a multi-method setting embracing positive scores derived from the Nilsson-scale, the CI-matrix and network analysis, it is necessary to ensure that identical input data sets are used. Hence, as the ANP only allows processing positive interaction scores, the two SDG target rankings provided by Weitz et al. (2018) (synergistic potential and progress control based on the CI-matrix) are re-calculated after deleting those SDG target interactions that show a negative interaction score (see Figure 9). The application of the ANP to the Weitz et al. (2018) case study data stringently followed all methodological steps examined with the hypothetical example as described in section 3.4. The test result with respect to the proposed heuristic of Mu et al. (2020) shows that the weighted supermatrix of the country case study is suitable for the task at hand.

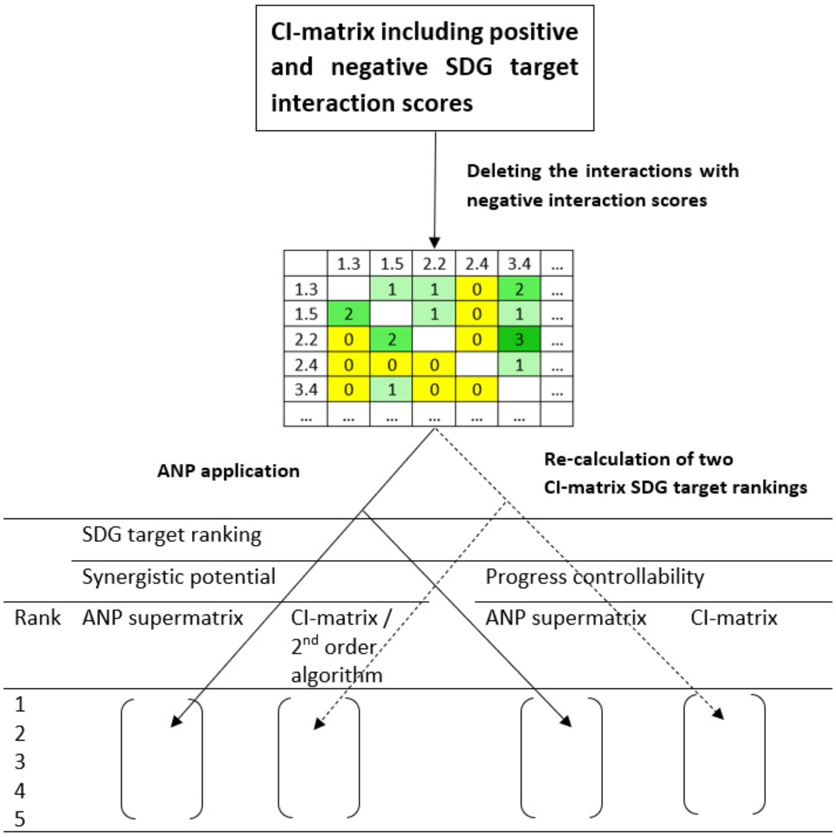


Figure 9: Overall approach for re-calculation of SDG target rankings

This procedure allows to align the CI-matrix SDG target rankings with the ANP SDG target rankings. The re-calculation was done as follows: Firstly, the total influence of the SDG targets on the second-order network was re-calculated as: $I_i^{Total} = D_i^{Out} + \frac{1}{2}\sum_{j \neq i} I_{ij} D_j^{Out}$, where D_i^{Out} is the out-degree of target *i*, I_{ij} is the interaction score of target *i* that influences target *j* and, finally, D_i^{Out} is the out-degree of target *j*. Of note here is the fact that the out-degree of a single SDG target is equal to its row-sum in the cross-impact matrix. Secondly, the SDG target ranking concerned with the total influence receiving from all other SDG targets with respect to the first-order network was re-calculated by taking the column-sum in the cross-impact matrix for each SDG target.

4 Results

4.1 Applied SDG entities interaction methods

The systematic literature review identified 30 methods applied in 93 analyzed publications. The methods were classified according to six distinct method categories as shown in Table 13.

Table 13: Classification of identified SDG entity interactions methods

Argumentative method category	
Method	Publications
Bayesian belief network (BBN)	Hall et al. (2018)
Causal loop diagram (CLD)	Zhang et al. (2016)
Cross-impact matrix (CI matrix)	Weitz et al. (2018); Zelinka and Amadei (2017); Kumar et al. (2018); Allen et al. (2019); Dawes (2020); Zaini and Akhtar (2019)
Structured elicitation of expert information (Expert)	Waage et al. (2015); Bhaduri et al. (2016); Hall et al. (2018); Allen et al. (2019); Hazarika and Jandl. (2019); Jaramillo et al. (2019); Wieser et al. (2019)
Nilsson scale (N Scale)	Nilsson et al. (2016); Hall et al. (2017); Weitz et al. (2018); Zelinka and Amadei (2017); Fader et al. (2018); McCollum et al. (2018); Singh et al. (2018); Allen et al. (2019); Hazarika and Jandl (2019); Jaramillo et al. (2019); Nerini et al. (2019)

Literature method category	
Method	Publications
Non-systematic literature review (Non-syst)	Bringezu (2018); Pandey and Kumar (2018); Morton et al. (2017); Wydra et al. (2019); Alcamo (2019); Recuero Virto (2018); Haines et al. (2017); Swamy et al. (2018); Hazarika and Jandl. (2019); Fisher et al. (2017); Manandhar et al. (2018)
Semi-systematic literature review (Semi-syst)	Bangert et al. (2017); Engström et al. (2018); Schroeder et al. (2019); Motta (2019); Hepp et al. (2019); Hanjra et al. (2016); Nerini et al. (2019); Nerini et al. (2018)
Systematic literature review (Syst)	Alcamo (2019); Blicharska et al. (2019); Davide et al. (2019)
Review of case studies (Case studies)	Velis et al. (2017); Alcamo (2019)
Linguistic method category	
Method	Publications
Keyword analysis (KWA)	Motta (2019); Nugent et al. (2018); Le Blanc (2015)
Simulation method category	
Method	Publications
Agent based modelling (ABM)	Wang et al. (2019)
Computable general equilibrium models (CGE)	Doelman et al. (2019); Matsumoto et al. (2019); Campagnolo and Davide (2019); Banerjee et al. (2019); Lucas et al. (2019); Schütze et al. (2017)
Energy system models (ESM)	Engström et al. (2019); Vandyck et al. (2018)
Integrated assessment models (IAM)	Doelman et al. (2019); Matsumoto et al. (2019); Zhang et al. (2019); Lucas et al. (2019); Fujimori et al. (2019); Hutton et al. (2018); Heck et al. (2018); Gao and Bryan (2017); Rao et al. (2016); Obersteiner et al. (2016); von Stechow et al. (2016)
System dynamics modelling (SD)	Pedercini et al. (2019); Allen, Metternich, Wiedmann, & Pedercini (2019); Dawes (2020); Pedercini et al. (2018); Spaiser et al. (2017); Collste et al. (2017)

Other quantitative method category	
Method	Publications
Accounting framework (Account)	Engström et al. (2018)
Network analysis (NWA)	Feng et al. (2019); Lusseau and Mancini (2019); Jaramillo et al. (2019); Allen et al. (2019); Kunčič (2019); McGowan et al. (2019); Dörgő et al. (2018); Lim et al (2018); Nugent et al. (2018); Mainali et al. (2018); Weitz et al. (2018); Zelinka and Amadei (2017); Le Blanc (2015); Jiménez-Aceituno et al. (2020); Sebestyén et al. (2019a) ; Sebestyén et al. (2019b)
Environmentally-extended multi-regional input-output models (IO)	Scherer et al. (2018); Hubacek et al. (2017)
Statistical method category	
Method	Publications
Advanced sustainability analysis (ASA)	Mainali et al. (2018)
Autoregressive distributive lag bounds test (ARDL)	Ngarava et al. (2019)
Correlation analysis (Corr)	Pradhan et al. (2017); Brecha (2019); Kroll et al. (2019); Donaires et al. (2019); Sebestyén et al. (2019a) ; Sebestyén et al. (2019b); Mainali et al. (2018); Ngarava et al. (2019)
Cox proportional hazards models (CPH)	Akinyemi et al. (2018)
Descriptive statistics (Descr)	Howden-Chapman et al. (2020)
Generalized method of moments (GMM)	Matthew et al. (2019); Shahbaz et al. (2019)
Joint correspondence analysis (JCA)	Ulman et al. (2018)
Linear mixed effect models (LMM)	Lusseau and Mancini (2019)
Pairwise granger causality test (PGC)	Ngarava et al. (2019)
Principal component analysis and Factor analysis (PCA&FA)	Feng et al. (2019); Sen and Ongsakul (2018); Donaires et al. (2019); Spaiser et al. (2017)
Quantile regression, bootstrapped (Q Reg)	Sinha et al. (2020)

Regression analysis (Reg)	Cluver et al. (2016); Obersteiner et al. (2016); Malerba (2019); Buonocore et al. (2019); Hall et al. (2017); Ulman et al. (2018); Ramos et al. (2018)

The category Statistical and Simulation embrace the most methods, together they account for 57% of the identified methods used for the analysis of SDG entity interactions. 22% of the publications apply a method belonging to the Statistical category, 21% use a method classified as Literature and 20% use a method that is sorted into the category Simulation (see pie chart in Figure 10). Remarkably, 17% of the publications use methods belonging to the category Other quantitative although this category only consists of three methods. This is because the network analysis is the most frequently applied method that has been reported in 16 publications (see Figure 10). Apart from the network analysis, integrated assessment models, non-systematic literature reviews, and scoring techniques are the most frequently used methods in the reviewed publications. The bar chart in Figure 10 shows the number of publications that applied a certain method. The pie-chart shows the portion of publications as a percentage of all the reviewed publications that used a method assigned to a certain method category. (ABM = Agent based modelling, Account = Accounting framework, ARDL = Autoregressive distributive lag bounds test, ASA = Advanced sustainability analysis, BNN = Bayesian belief network, Case studies = Review of case studies, CGE = Computable general equilibrium models, CI matrix = Cross-impact matrix, CLD = Causal loop diagram, Corr = Correlation analysis, CPH = Cox proportional hazards models, Descr = Descriptive statistics, ESM = Energy system models, Expert = Structured elicitation of expert information, GMM = Generalized method of moments, IAM = Integrated assessment models, IO = Environmentally-extended multi-regional input-output models, JCA = Joint correspondence analysis, KWA = Keyword analysis, LMM = Linear mixed effect models, N scale = Nilsson scale, Non-syst = Non-systematic literature review, NWA = Network analysis, PCA&FA = Principal component analysis and Factor analysis, PGC = Pairwise granger causality test, Q Reg = Quantile regression, bootstrapped, Reg = Regression analysis, SD = System dynamics modelling, Semi-syst = Semi-systematic literature review, Syst = Systematic literature review).

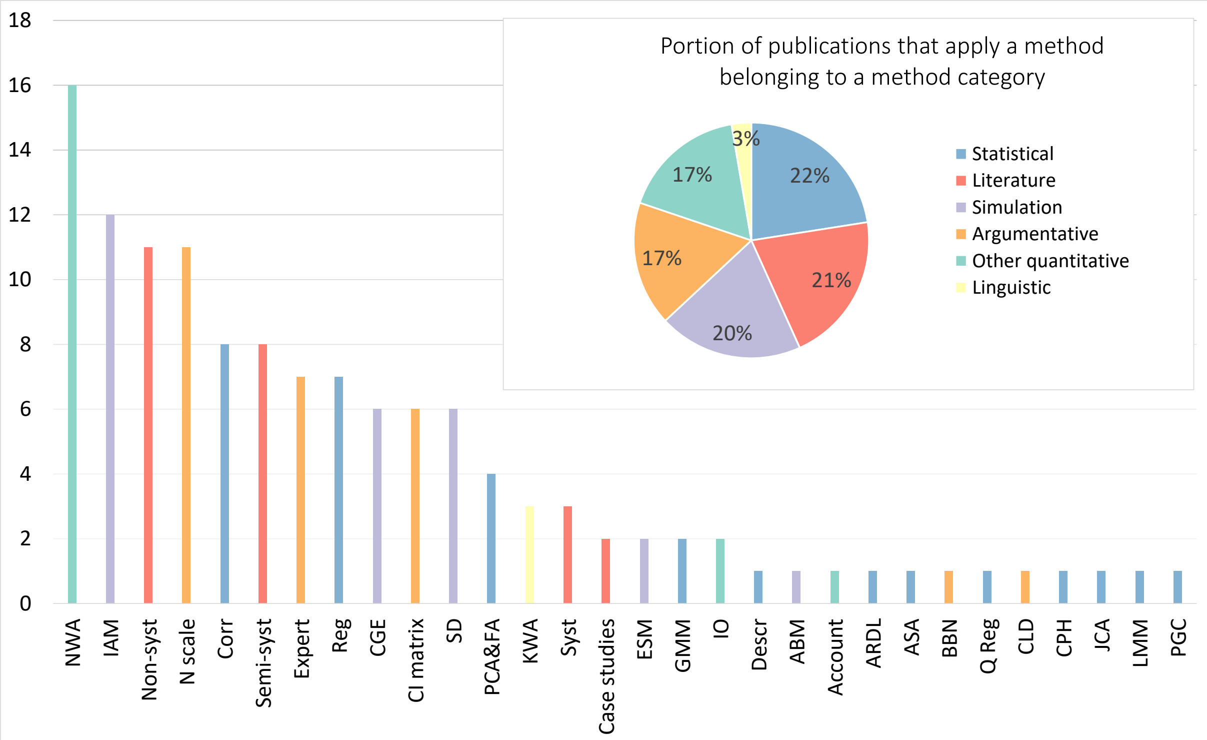


Figure 10: Number of publications applying a single method and portion of publications applying a method belonging to a method category

28% of the reviewed publications report a multi-method approach indicating the application of more than one method, whereas 18% of the publications use two methods, 9% three methods and 1% apply four methods. A closer look onto the multi-method approaches shows that specific bundles of methods were used combined and reported in different publications. Evidently, the bundle of methods embracing a scoring with the Nilsson scale and the subsequent application of a CI-matrix and a network analysis as well as the combined application of structured elicitation of expert information and scoring with the Nilsson scale are three times reported which is the most often of all method bundles. However, these bundles overlap and are reported in publications applying three or four methods.

4.2 Evaluation of SDG entities interaction methods

The results of the expert's assessment as documented in section 3.2 is shown in Figure 11. The fulfillment rate of a single method with respect to a single criteria group is expressed by the share of valued T=true criteria and the total amount of criteria belonging to this criteria group. Considering all four criteria groups, the maximal fulfillment rate that can be achieved by a single method is 4. A fulfillment rate of 1 of a method for a single criteria group indicates that the method was valued with T=true for all criteria of this group.

The criteria group ‘Effects’ allows to detect effects between SDG entities and to specify the effects’ direction, polarity and degree. Furthermore, a criterion evaluating the detection of feedback loops is included in this group, which is presented blue in Figure 11. The criteria group ‘Interdisciplinary sensitivity’ includes criteria assessing the methods’ ability to process different kinds of information, such as qualitative information, quantitative information, implicit knowledge as well as subjective preferences and/or values. This criteria group is shown in dark orange in Figure 11. The criteria group ‘Collaboration and systems thinking’ allows to assess methods with respect to their ability to include information about the certainty of results, to evaluate if the method operates transparently and to assess if the method produces results that are easy to interpret. The criteria group ‘Collaboration and systems thinking’ is presented grey in Figure 11. The criteria group ‘Practicability of application’ (orange in Figure 11) includes criteria assessing several issues relating to what is needed for application (e.g., specialized knowledge of methodology or computer-based support) and some other method’s properties (e.g., adaptability to different scales or if it can be used in a collaborative setting). The criterion time effort (c19) which is also part of the criteria group ‘Practicability of application’, is excluded from the evaluation shown in Figure 11, as it was not assessed with the binary scale. More respective details can be found in Publication I in section 8.1.

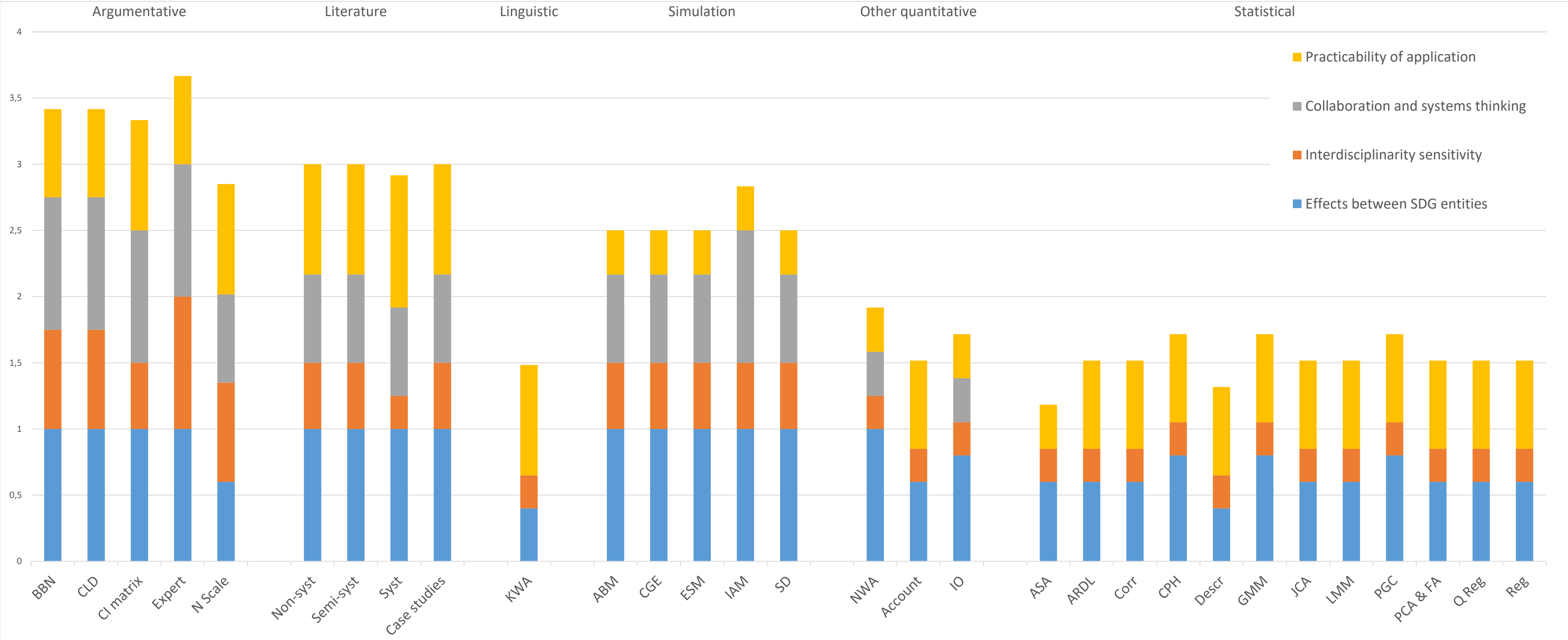


Figure 11: Fulfillment rates of SDG entities interaction methods for the criteria groups and arranged by method categories

The evaluation results show that methods belonging to the method category Argumentative perform best in terms of their total fulfillment rates considering all criteria groups. The results also show that, methods belonging to the method categories Argumentative, Literature and Simulation, have the ability to give more detailed information on effects between SDG entities and thus are useful for creating an understanding of the dependencies given in the analyzed human-environment system. In contrast to the methods of the other categories, the methods of the Linguistic and the Statistical group do not allow to foster collaboration and systems thinking of the applicants (e.g., due to their not-transparent operation, c11).

While the methods belonging to the Argumentative, Literature, and Simulation category form a rather uniform group within their category in terms of their assessment, methods belonging to the Other quantitative category and to the Statistical category give a much more mixed picture. On a method level, the method Expert (Structured elicitation of expert information) fulfills 16 out of 18 criteria and hence is the one with the best performance in this regard. It only shows weaknesses regarding their practicability of application. Conversely, the method with the worst performance is ASA (Advanced sustainability analysis) which was assessed with the fulfillment of six criteria only.

4.3 Overview of uncertainty issues associated with the AHP

Several methods were screened in Publication I with respect to their ability to give information about the certainty of their result. In the context of the application of the AHP, the critical literature review (see section 3.1.2) led to the identification of 12 major uncertainty issues. These uncertainty issues are categorized with respect to the four different steps of multi-criteria decision making (Belton & Stewart, 2002) considering group decision making as well (see Table 14). From the short summaries provided for each identified uncertainty issue it becomes evident that many meta-choices have to be made to solve a decision problem, while the involved human judgements are subject to numerous cognitive and motivational biases (Ferretti & Montibeller, 2016; Montibeller & von Winterfeldt, 2015). For example, the AHP user has to choose which scale presentation mode (verbal or numeric) appears to be more suitable for elicitating judgements. This introduces uncertainty associated with the response mode and is part of the multi-criteria decision making step ‘weights valuation’ (see Table 14)

Table 14: Overview of uncertainty issues associated with the AHP

	Steps of MCDM	Embedded uncertainty issues
Human input - Meta-choices and human behavioral aspects	Problem modelling	**Uncertainty associated with modelling** – general inability of models to represent the problem it attempts to structure (Maier et al., 2008) **Uncertainty associated with the development of the model structure** – determination of structure of a numerical, hierarchical induction model; how to include which elements (e.g., criteria/sub-criteria, 'wash criteria' or 'future aspects') to capture the real-world complexities? (Brugha, 1998, 2004; Finan & Hurley, 2002; Levary & Wan, 1998; Maleki & Zahir, 2013; Saaty, 2007; Saaty & Begicevic, 2010; Warren, 2006) **Uncertainty associated with the incorporation of important, but 'unknown' factors** – how to include important, but only suspected and not explicitly articulated factors into the problem modelling? (Ozdemir & Saaty, 2006)
Human input - Meta-choices and human behavioral aspects	Weights valuation	**Measurement theoretical debate** – is the original preference measurement scale (linear; Saaty-scale) a ratio scale? (Barzilai, 2001, 2006; Bernasconi, Choirat, & Seri, 2010, 2011; Salo & Hämäläinen, 1997)
Human input - Meta-choices and human behavioral aspects	Weights valuation	**Uncertainty associated with the used scale type** – which scale (e.g., linear (Saaty-scale), power or logarithmic) is used to elicit the pairwise comparisons? Should the used scale be adapted to the individual decision makers' characteristic? (Beynon, 2002a; Choo &Wedley, 2010; Dong et al., 2013; Dong et al., 2008; Finan & Hurley, 1999; Harker, 1987a; Leskinen, 2001; Liang et al., 2008; Saaty & Ozdemir, 2003)
Human input - Meta-choices and human behavioral aspects	Weights valuation	**Uncertainty associated with the response mode** – which scale presentation-mode (e.g., verbal or numeric) is used to elicit the pairwise comparisons from the decision makers? (Huizingh & Vrolijk, 1997; Pöyhönen, Hämäläinen, & Salo, 1997; Webber, Apostolou, & Hassell, 1997)
Human input - Meta-choices and human behavioral aspects	Weights valuation	**Uncertainty associated with vague judgements** – how (e.g., interval judgements or fuzzy set theory) to incorporate the imprecision of human judgement into the process? (Deng, 1999; Leung & Cao, 2000; Mikhailov, 2004a; Moreno-Jimenez & Vargas, 1993; Saaty & Tran, 2007; Sadiq & Tesfamariam, 2009; Sugihara & Tanaka, 2001; Zhü, 2014)
Human input - Meta-choices and human behavioral aspects	Weights valuation	**Uncertainty associated with incomplete pairwise comparison matrices** – how to deal (e.g., Monte-Carlo simulation approaches or optimization methods) with incomplete pairwise comparison matrices? (Bozóki, Fülöp, & Rónyai, 2010; Carmone Jr, Kara, & Zanakis, 1997; Fedrizzi & Giove, 2007; Harker, 1987b; Hua, Gong, & Xu, 2008; Kwiesielewicz & Van Uden, 2003; Srdjevic, Srdjevic, & Blagojevic, 2014; Wedley, 1993)

Human input - Meta-choices and human behavioral aspects	Weights valuation (continued)	**Uncertainty associated with consistency measurement –** how to check (e.g., usage of which random indices?) that the provided decision makers' judgments are logical, reasonable and non-random? In the case the judgements appear random, what kinds of modifications are feasible? How to ensure group consistency? (Cao, Leung, & Law, 2008; Dadkhah & Zahedi, 1993; Dodd, Donegan, & McMaster, 1993; Donegan & Dodd, 1991; Grošelj & Stirn, 2012; Ishizaka & Lusti, 2004; Karapetrovic & Rosenbloom, 1999; Kwiesielewicz & van Uden, 2004; Lamata & Alonso, 2006; Moreno-Jiménez et al., 2008; Ramík & Korviny, 2010; Zeshui & Cuiping, 1999)
		Uncertainty associated with priority derivation – how (e.g., synthesis mode, normalization procedure and the issue of rank preservation and reversal) to derive preference values from the pairwise comparison matrices? Does the eigenvalue-method is sufficient to derive priority? (Bana e Costa & Vansnick, 2008; Barzilai & Golany, 1994; Belton & Gear, 1985; Belton & Gear, 1983; Choo & Wedley, 2004; Dyer, 1990; Harker & Vargas, 1990; Holder, 1990; Hung et al., 2009; Huo, Lan, & Wang, 2011; Ishizaka & Labib, 2011a; Ishizaka & Lusti, 2006; Johnson, Beine, & Wang, 1979; Maleki & Zahir, 2013; Millet & Saaty, 2000; Saaty & Vargas, 1984; Saaty & Vargas, 1993; Triantaphyllou, 2001)
	Weights aggregation	**Uncertainty associated with the aggregation mode between the different levels of the problem modelling hierarchy** – how (additive or multiplicative) to aggregate preferences to an overall preference vector? (Choo, Schoner, & Wedley, 1999; Stam & Duarte Silva, 2003; Triantaphyllou, 2001)
	Sensitivity analysis	**Uncertainty associated with the type of sensitivity analysis** – how (e.g., variation in judgements or one/multi-dimensional simulation approaches) to conduct an appropriate sensitivity analysis? (Butler, Jia, & Dyer, 1997; Chen & Kocaoglu, 2008; May et al., 2013; Triantaphyllou & Sanchez, 1997)
	Group decision making	**Uncertainty associated with the combination procedure of several decision makers' judgments** – how (e.g., geometric mean on pairwise comparisons, weighted arithmetic mean on derived priorities or consensus models) to derive an appropriate group aggregation? (Altuzarra, Moreno-Jiménez, & Salvador, 2007; Dong et al., 2010; Forman & Peniwati, 1998; Grošelj et al., 2015; Ishizaka & Labib, 2011a; Mikhailov, 2004b; Ossadnik et al., 2016; Saaty & Peniwati, 2013; Saaty & Vargas, 2012)

4.4 A comprehensive uncertainty analysis procedure and computed uncertainty scenarios

The developed comprehensive uncertainty analysis procedure was developed and applied in Publication II. For easing the reading of the methodological description, the developed comprehensive uncertainty analysis procedure is presented in section 3.3. The quantification part of the comprehensive uncertainty analysis embraces the computation of USs. As presented in section 3.3.2, 14 USs including different combinations of the four identified uncertainties (see Table 9) and two scenarios only including the respective versions of the original AHP were computed for the heating system purchase problem. Due to fact that the simulation experiment was based on random pairwise comparison matrices for the determined PTs, a huge number of different combinations of possible random pairwise comparison matrices for the involved PTs was possible, which was considered by an amount of 531 441 total simulation runs for each the scenarios considering the original AHP and the different USs. For a precise mathematical description of the algorithms selecting and further combination of different random pairwise comparison data reflecting different PT of the family members, please see Publication II in the appendix.

The basic idea behind the calculation of the USs is to examine a sensitivity analysis (see section 3.3.2) to check the quantitative impact of uncertainties on the AHP model result compared with the AHP model result neglecting uncertainties considering the total simulation runs. Hence, the 'overall uncertainty' measure is expressed as percentages that indicate if and how often the inclusion of a specific US changes the rank of the best alternative given by the original AHP without considering any uncertainties, i.e., in % rank reversal. As the alternatives Logs and Wood pellets show performance advantages under the criteria Costs and CO_2-emissions (see Table 7) and the PTs of all family members are determined to evaluate these two alternatives equally and in line with the structure embedded in the quantitative data (variant II), the determined group preference structure magnifies the performance advantages of the Logs and Wood pellets with respect to the criteria Costs and CO_2-emissions. As a result, the implementation of USs under variant II does not lead to any rank reversal. Hence, variant II is not being further discussed in this thesis.

4.4.1 Descriptive statistics of absolute maximal impact of uncertainty scenarios

The simulation experiment shows that for the cases a rank reversal occurs, the absolute maximal impact of an US on an alternative's evaluation is very small. Using the geometric mean group aggregation method for the US5 for variant I results in approximately 0.03 (highlighted bold in Table 15). This indicates that the priorities of the single alternatives that show a rank reversal are very similar.

Table 15: Descriptive statistics of absolute maximal impact of USs related to the results derived from the original AHP associated with a case of rank reversal over all alternatives

	Group aggregation method											
	Weighted arithmetic mean (wam)						Geometric mean (gm)					
	Mean		SD		Max		Mean		SD		Max	
Uncertainty Scenarios (US)	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III
US1	0.00617	0.00371	0.00467	0.00276	0.02145	0.01439	0.00731	0.00446	0.00489	0.00307	0.02455	0.01418
US2	0.00314	0.00489	0.00232	0.00331	0.01145	0.01740	0.00457	0.00607	0.00351	0.00405	0.01509	0.02117
US3	0.00913	0.00780	0.00438	0.00443	0.01895	0.02093	0.00922	0.00776	0.00426	0.00428	0.01760	0.01881
US4	0.00768	0.00822	0.00528	0.00574	**0.02385**	0.02714	0.00841	0.00776	0.00567	0.00370	0.02885	0.01996
US5	0.00690	0.00491	0.00533	0.00338	0.02362	0.01692	0.01050	0.00634	0.00646	0.00444	**0.03012**	0.02100
US6	0.00732	0.00554	0.00494	0.00388	0.02383	0.02045	0.00694	0.00512	0.00471	0.00369	0.02271	0.01995
US7	0.00836	0.00916	0.00599	0.00675	0.02342	**0.02850**	0.00765	0.00848	0.00504	0.00515	0.02114	**0.02439**

4.4.2 Deriving advice from the rank reversals of the uncertainty scenarios

Over all variants and over both group aggregation methods, Figure 12 (b) and d)) shows that the more uncertainties involved in an US the higher the 'overall uncertainty' measure, which itself differs in the level of positive linear correlation. Apparently, over both group aggregation methods, the R^2 of variant III is smaller than the R^2 of variant I. For example, the 'overall uncertainty' measure using the weighted arithmetic mean group aggregation method for either variant I or variant III is presented with US1 in Figure 12 a). Additionally, Figure 12 (a) and c)) shows that the geometric mean group aggregation method principally causes larger shares of rank reversal; it leads in every single US over both variants to a larger 'overall uncertainty' measure.

As shown in Figure 12 (a) and c)), similar shares of rank reversal occur within a single variant for USs including differing number of uncertainties and varying uncertainties. For example, for variant I, computing US3 using the weighted arithmetic mean group aggregation method and US1 using the geometric mean group aggregation method lead to comparable results. For variant III, US5 using the weighted arithmetic mean group aggregation method and US6 using the geometric mean group aggregation method results in comparable shares of rank reversal. With respect to the 'overall uncertainty' measure, the shares of rank reversal vary over the computed USs. The maximal share of rank reversal (35.11% of total simulation runs n = 531 441) using the weighted arithmetic mean group aggregation method occurs in variant I implementing US4 (Figure 12 a)). Respectively, using the geometric mean group aggregation method, US7 computing variant III gives the maximum of 51.33% (Figure 12 c)). Interpreting this from a normative point of view, it would be alarming. However, looking at the sizes of the maximal impact of USs related to the results derived from the original AHP associated with a case of rank reversal over all alternatives (see Table 15), it becomes from a practitioner's point of view relativized.

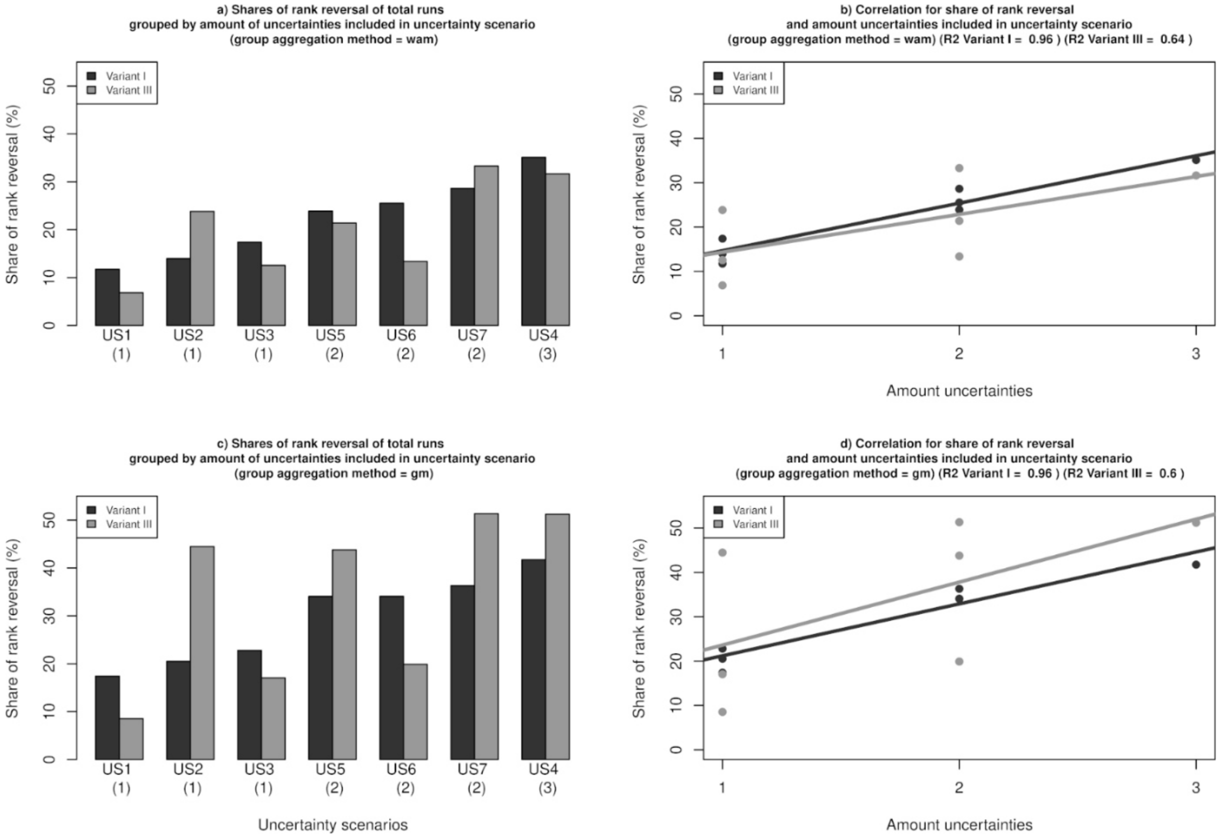


Figure 12: 'Overall uncertainty' measure of uncertainty scenarios (USs) and correlation with amount of uncertainties for variant I and variant III

With respect to the 'overall uncertainty' measures computed (Figure 12), the following uncertainty aspects should be addressed to formulate advice: 1) Nearly equal shares of rank reversal for different USs with differing number of uncertainties and varying uncertainties within a single variant can be observed. The results indicate that different uncertainties involved may lead to comparable shares of rank reversals. Hence, it is not obvious to which aspect of uncertainty should be given more attention within the decision-making process, which implies that under limited resources (e.g., time, budget and staff) it may be necessary to negotiate with the decision makers which uncertainties should/can be addressed by which methodological extension. 2) The geometric mean group aggregation method principally causes larger shares of rank reversal as the weighted arithmetic mean group aggregation method. This result advises that applying the weighted arithmetic mean group aggregation method leads to a more robust alternative ranking with respect to the purchase decision problem compared to considering the geometric mean group aggregation method.

4.5 SDG target ranking computed with the ANP

As indicated in section 3.4, two ANP models were employed to compute two SDG target rankings. The first ranking sorts the SDG targets with respect to their synergistic potential, i.e., due to their overall positive influence on all other SDG targets in the SDG target network. The second ranking orders the SDG targets regarding their control over their own progress, i.e., due to the positive influence received from all the other SDG targets in the SDG target network. The relative importance or priority of the SDG targets is shown in Table 16. The higher the priority, the better the rank. Regarding the progress controllability ranking, it is important to note here, that a high overall level of influence received from all other SDG targets suggests that less control is inherent to the SDG target regarding its own progress, i.e., the worst ranked SDG target is the most preferred one in this context. The interpretation of the rankings with respect to the country case study is done as part of the multi-method application in section 4.8.

Table 16: ANP results: SDG target rankings

	Synergistic potential		Progress controllability	
Rank	SDG target	Priority	SDG target	Priority
1	16.6	0.067946	1.5	0.065546
2	8.4	0.060716	13.1	0.052345
3	12.1	0.060336	2.4	0.049379
4	8.5	0.045566	15.5	0.046410
5	12.5	0.043292	6.6	0.041714
6	9.5	0.042887	10.1	0.040204
7	4.4	0.042869	8.5	0.037492
8	5.5	0.041932	12.1	0.037234
9	9.4	0.040456	15.2	0.037073
10	7.3	0.037740	6.5	0.034224
11	13.1	0.036779	13.2	0.033470
12	13.2	0.035138	1.3	0.033240
13	1.5	0.034357	8.4	0.032216
14	1.3	0.034000	4.4	0.029821
15	11.2	0.032496	9.4	0.029552
16	16.4	0.031316	10.7	0.029033
17	2.4	0.029822	3.4	0.028803
18	5.4	0.028510	11.2	0.026900
19	7.2	0.028324	11.1	0.026388
20	6.5	0.026843	14.1	0.026053
21	4.1	0.025938	5.5	0.024441
22	10.7	0.017785	12.5	0.023927
23	11.1	0.017195	2.2	0.023540
24	2.2	0.016783	17.13	0.022874
25	17.13	0.016736	14.4	0.021721
26	15.5	0.015570	7.3	0.020780
27	14.4	0.015274	3.8	0.019732
28	14.1	0.014927	16.6	0.018545
29	10.1	0.014226	9.5	0.018408
30	15.2	0.010882	5.4	0.018029
31	3.8	0.009571	4.1	0.016756
32	17.11	0.009246	7.2	0.014747
33	6.6	0.008726	16.4	0.012182
34	3.4	0.005818	17.11	0.007223

4.6 Comparison of SDG target rankings

Weitz et al. (2018) pose the question of whether or not it is worthwhile to account for 3rd order influence and beyond in SDG target networks, encouraging to check if it makes a difference to consider more indirect SDG target interactions beyond the 2nd order influence when elaborating SDG target rankings. Therefore, the ANP was applied to analyze the n-order influence of the SDG target network.

Table 17 compares the top 5 ranked SDG targets of the re-calculated CI-matrix / 2nd order algorithm and the ANP for the two rankings for the case study data. The color indicates whether the SDG target is ranked identically for both analytical methods (green), the SDG target is included in the top 5 of both approaches (cyan) or not (red).

Table 17: Comparison of top 5 ranked SDG targets of the re-calculated CI-matrix / 2nd order algorithm and the ANP with respect to different SDG target rankings

	SDG target ranking			
	Synergistic potential		Progress controllability	
Rank	ANP supermatrix	CI-matrix / 2nd order algorithm	ANP supermatrix	CI-matrix
1	16.6	16.6	1.5	1.5
2	8.4	12.1	13.1	2.4
3	12.1	8.4	2.4	13.1
4	8.5	12.5	15.5	13.2
5	12.5	9.5	6.6	12.1

Overall, it can be seen that the ANP results are close to both SDG target rankings calculated by the CI-matrix approaches. The top-ranked SDG target is the same for each of the two rankings. For the rankings concerning the synergistic potential, the ANP ranks SDG target 8.5th 4th, whereas it is not part of the top 5 derived from the CI-matrix / 2nd order algorithm, where it is ranked 8th. Also of note is the fact that SDG target 9.5 is ranked 6th applying the ANP. With respect to the rankings concerned with the progress controllability, the ANP ranks SDG target 15.5 4th and SDG target 6.6 5th, whereas neither are included in the top 5 rankings calculated by the CI-matrix / 2nd order algorithm. SDG target 15.5 is ranked 7th by the CI-matrix / 2nd order algorithm and SDG target 4.4 is 12th. Conversely, the CI-matrix / 2nd order algorithm place SDG target 13.2 and SDG target 12.1 in the top 5, whereas they are ranked 11th and 8th respectively by the ANP.

4.7 Analytical methods’ potential to formulate policy advice

In considering the analytic dimension of the applied methods, their potential to formulate policy advice is evaluated and to which policy challenges (Bennich et al., 2020) the policy advice can respond to. As shown in Table 18, the results of the various analytical methods provide a different perspective on the potential policy advices. The CI-matrix, the supermatrix of the ANP as well as network analysis methods produce results that respond to the policy challenge of ‘policy prioritization’ as they are instruments guiding the identification of the most promising entry point into the network of SDG interdependencies. Furthermore, the network analysis methods allow the identification of political actors that are responsible for the achievement of specific SDG targets and hence the prioritization of such institutions’ stakeholder collaboration. Additionally, they create results that respond to the policy challenge ‘integrated perspective’ in the sense of promoting a systemic thinking and learning of the involved decision makers.

Table 18: Potential of the analytical methods to formulate policy advice

Policy challenges	Results & policy advice	Analytical method
Policy prioritization	**SDG target ranking - synergistic potential**: Approximation of issue-based entry point into the network of SDG interdependencies	**CI-matrix**: The SDG targets can be ranked by their overall positive influence on all other SDG targets considering the 1st order influence in the SDG target network **CI-matrix / 2nd order algorithm**: The SDG targets are ranked by their overall positive influence on all other SDG targets considering 2nd order influence in the SDG target network (Weitz et al. 2018) **ANP supermatrix**: The SDG targets can be ranked by their overall positive influence on all other SDG targets considering the n-order influence in the SDG target network
	SDG target ranking - progress controllability: Identification of SDG targets that show overall low control over their own progress	**CI-matrix**: The SDG targets can be ranked by the overall positive influence received from all other SDG targets considering the 1st order influence in the SDG target network **ANP supermatrix**: The SDG targets can be ranked by the overall positive influence received from all other SDG targets considering the n-order influence in the SDG target network
	Visualization: Identification and prioritization of stakeholder collaboration	**Network analysis**: The identification and prioritization of stakeholder collaboration can be supported by visualizing the direct influence from and on other SDG targets from the perspective of a single SDG target
Policy prioritization and integrated perspective	**SDG target clusters of 'positive mutual influence':** Identification of the cluster's stakeholder and prioritization of referring collaboration. Enhancing the system understanding	**Network analysis**: Using network analysis software for the identification of clusters of 'positive mutual influence', i.e., the SDG targets included show mostly synergies
Integrated perspective	**Sub-Networks of indivisible and constraining / counteracting interactions:** Enhancing the system understanding by identifying effective SDG targets and influence paths	**Network analysis**: The sub-networks (of indivisible and constraining / counteracting interactions) help to focus on those SDG target interactions that are important due to their multiple and strong influence on other SDG targets

The ANP supermatrix and the CI-matrix allow calculating the same two SDG target rankings (synergistic potential and progress controllability) (see Table 18). Weitz et al. (2018) argue that the calculation of the influence of single SDGs considering only direct SDG target interactions provides insufficient information to effectively guide priority-setting of SDG implementation action. Both CI-matrix approaches (CI-matrix and CI-matrix / 2nd order algorithm) presented provide a ranking to the synergistic potential of the SDG targets differing only in their order of influence within the SDG target network that is considered (Table 18). The CI-matrix / 2nd order algorithm method also processes indirect SDG target interactions by referring to the 2nd order influence and is therefore a more suitable SDG target ranking as the one provided by the classical CI-matrix because it includes a better information base. As with the two CI-matrix approaches, the ANP allows the ranking of SDG targets due to their synergistic potential. The ANP calculates the positive influence of the n-order SDG target network (see section 3.4), which allows the processing of more indirect SDG target interactions and leading to a more sensitive SDG target ranking, that might change when additional interactions are introduced to the network. Therefore, to guide policymaking on how to approach the SDGs without losing the indivisible whole idea, it is arguable that the ANP is more suitable to identify possible entry points of the SDG network than the two CI-matrix approaches. Additionally, both, the CI-matrix approach relying on the 1st order influence as well as the ANP provide guidance regarding whether progress on an SDG target is at risk of being neutralized or halted by progress on other SDG targets. The results of the SDG target rankings indicate the control possible over the SDG targets' progress. Translating this into policy advice means that actual SDG implementation should focus on those SDG targets that are largely autonomous, when it comes to their own progress as this significantly reduces the randomness of outcomes of any realized SDG implementation actions.

The network analysis methods presented allow to identify and to prioritize stakeholder collaboration as well as enhanced system understanding for policymakers. The identified sub-networks support the detection of influence paths within the SDG target network allowing to consider cost efficiency reflections of SDG implementation at a very basic level. Goal attainment of a specific SDG target may be approached by various influence paths embracing differing SDG targets that trigger this influence path. Therefore, several SDG implementation actions may be chosen to approach these different SDG targets which, in turn, reveal that the costs of a single SDG implementation action become a relevant factor for implementation planning. Approaching clusters of 'positive mutual influence' allows the identification of areas where success can be rapidly achieved regarding SDG goal attainment, while also revealing the negative links (trade-offs) between clusters that are crucial elements within the network. Additionally, the political actors playing a role within these clusters can be better identified as stakeholders and may build strategic partnerships (Weitz et al. 2018).

4.8 Improving the overall quality of the policy advice

The combination of different analytical methods comprises advantages and disadvantages in their ability to improve the quality of the provided policy advice, which raises the question of a suitable setting. Policy advice being generically formulated in terms of the 'potential' insights and improvements from a methodological point of view is inadequate to guide policymaking for a specific situation. Translating the analytical methods' results into concrete policy advice needs to consider on one of the four basic types of advice that can be given to decision-makers: 'Recommend For', Recommend Against', 'Decision Support' and 'Information' (Dalal & Bonaccio, 2010).

'**Recommend For**' is the typical conceptualization of advice in the decision-making literature. In the context of SDG implementation, it could be the advice for choosing a specific SDG target as an entry point of the SDG target network or a recommendation for stakeholder collaboration. In the context of the case study application a policy advice could be formulated: 'Start SDG implementation by approaching **SDG target 16.6** (*Effective institutions*)', because it best supports the positive interactions in the SDG target network'. Relying on the SDG target rankings produced by the ANP provide a more solid information base, as it includes more indirect SDG target interactions, than the rankings provided by the CI-matrix methods. SDG target 16.6 is identified by the ANP as the target with the highest synergistic potential in the whole network (Table 16). Conversely, '**Recommend Against**' could help to identify SDG targets that should be perhaps not prioritized in a specific SDG implementation due to their less control over their own progress (e.g., SDG target 1.5 in the progress controllability ranking, Table 17).

The advices ‘**Decision Support**’ and ‘**Information**’ supplement the decision-making process by providing information about the interactions of a specific SDG target within a network and by recommending different procedures regarding how to decide where to start SDG implementation. In the context of the case study application a policy advice could be formulated: ‘Compare the implementation costs of **SDG target 16.6** (*Effective institutions*) and **SDG target 16.4** (*illicit financial/arms flow*)’, because there might be different preferable compromises of implementation costs and direct/indirect approaching of SDG target 16.6. In particular the influence paths in the sub-network of indivisible interactions indicate to compare the implementation costs for SDG target 16.4 and SDG target 16.6 as they have bidirectional influence on each other and as it might be that the indirect support for SDG target 16.6 through an SDG implementation option targeting SDG target 16.4 is cheaper as the implementation option directly approaching SDG target 16.6. Furthermore, for these two SDG targets their inherent control over their own progress based on the ANP results could be taken into consideration when starting the SDG implementation. In the context of the case study example, a policy advice could be formulated: ‘Consider the inherent control over their own progress of **SDG target 16.6** (*Effective institutions*) and **SDG target 16.4** (*illicit financial/arms flow*)’, because relatively less inherent control can introduce randomness of outcomes of realized SDG implementation actions. A high overall level of influence received from all other SDG targets suggests that less control is inherent to the SDG target regarding its own progress. Hence, it is easier to achieve these heavily influenced SDG targets by ensuring the achievement of those SDG targets that exert a positive interaction.

The SDG target ranking showing the progress controllability (Table 16) suggests that this dimension could be neglected in the application as both SDG targets are almost similar ranked with respect to their control over their own progress (SDG target 16.6 is ranked 28th and SDG target 16.4 33th).

Network analysis methods allow to visualize the importance of actors in a network from the perspective of a single SDG target. This can help to identify and prioritize stakeholders with whom collaboration can be beneficial. In the context of the case study example, and if SDG target 16.6 is chosen to be approached directly, the framing as concrete policy advice could be as follows: ‘Analyse if progress on **SDG target 16.6** (*Effective institutions*) may impede progress of other SDG targets or if progress on other SDG targets may prevent progress on **SDG target 16.6** (*Effective institutions*)', because there might be resistance or the need to negotiate. In this context, the collaboration with those actors that are responsible for the achievement of specific SDG targets can help to improve the coordination process or can lead to a dilution of the desired implementation effects.

Referring to the case study application, these simplified examples demonstrate that the combination of different analytical methods improves the overall quality of the formulated policy advice regarding its scope and methodological profoundness. Additionally, the presented framing of methodological results as concrete advice may allow to enhance accepting and utilizing it (Bonaccio & Dalal, 2006; Dalal & Bonaccio, 2010).

5 Discussion

5.1 Suitability of collaborative planning methods to support decision making

The systematic literature review as part of Publication I and answering RQ1 (Which methods were used to evaluate interactions among SDG entities?) led to the identification of a broad range of 30 methods applied in 93 analyzed publications. The methods were classified according to six distinct categories (Argumentative, Literature, Linguistic, Simulation, Other quantitative and Statistical) (see also Table 13). On the level of a single publication, the identified methods may differ compared to other reviews. For example, Table 19 compares the identified methods applied in the publication of Weitz et al. (2018) as reported by different reviews.

Table 19: Comparison of results of different reviews with respect to the identified methods applied in Weitz et al. (2018)

Reviews	Applied methods' sequence		
This thesis	Scoring with Nilsson-scale	Cross-impact matrix	Network analysis
Bennich et al. (2020)	Document analysis	Cross-impact analysis	Network analysis
Allen et al. (2021)		Cross-matrix analysis	Network analysis

This differing analysis could be a consequence of the granularity of the clustering of the identified methods or due to a different understanding where a method starts and where a method ends. However, Bennich et al. (2020) report nine methods of analysis, whereas Allen et al. (2021) identified 22 scientific approaches and finally the review presented in Publication I identified 30 methods overall.

To tackle RQ2 (How do the methods used for the evaluation of interactions among SDG entities differ?), a set of evaluation criteria was developed and applied in Publication I. For 18 of the 19 criteria a binary scale (T=true, F=false) was adopted to assess the performance of the single methods. A limitation of the research stems from this decision as the choice for a more nuanced scale would allow to generate a more detailed picture of the methods properties. However, the binary scale was chosen because it is the best compromise to detect basic differences of the methods and to be simply and fast-forward applied by the author team.

Methods analyzing interactions among SDG entities can be evaluated in several ways. Other authors developed broad, desirable qualities embracing scalability, replicability, specificity and directionality that should be adhered to by the second generation of SDG network estimation techniques (Ospina-Forero, Castañeda, & Guerrero, 2020) or highlight the need for replicability, context sensitivity as well as the ability to rank SDG targets to formulate concrete policy advice for specific situations (Breuer et al., 2019). Additionally, Alcamo et al. (2020) presented the four characteristics of i) Level of external data requirements, ii) Level of expert judgement, iii) Interactive and iv) Spatially explicit results to compare methods used for analyzing SDG interactions in different case studies. However, the perceived difference of assessed methods is to some extend pre-determined by the evaluation criteria chosen.

In Publication III, it is shown that analytical methods allow to advise and guide SDG implementation based on their methodological results. This is a difficult task as the 'methodological profoundness' of such an advice inherently depends on the methodological understanding of the approach used and of its limitations. Answering RQ8 (How do the different SDG analytical methods differ with respect to their potential to formulate policy advice?), the analytical methods differ regarding their potential to formulate policy advice. As shown in Table 18, the ANP supermatrix and the CI-matrix allow calculating the same two SDG target rankings (synergistic potential and progress controllability). The network analysis methods presented allow to identify and to prioritize stakeholder collaboration as well as enhanced system understanding for policymakers. The identified sub-networks support the detection of influence paths within the SDG target network allowing to consider cost efficiency reflections of SDG implementation at a very basic level. However, the preferred policy advice and therefore the producing analytical method can only be chosen considering the progress and requirements of a specific SDG implementation setting.

5.2 Sustainability problems and uncertainty

The application of IT-supported collaborative planning methods for solving sustainability problems, in particular the usage of MCDM methods such as the AHP or ANP is inherently linked to the occurrence of uncertainty issues (Ishizaka & Nemery, 2013; Whitaker, 2007a, 2007b). RQ3 (Which uncertainty issues occur in decision-making practice using AHP?) as part of Publication II has been answered by conducting a critical literature review to identify the most significant uncertainty issues in the field. 12 major uncertainty issues associated with the application of the AHP embracing the collaborative planning phases problem modelling and problem solving (Table 20) were identified.

Table 20: Uncertainty issues associated with the AHP and collaborative planning phases

Collaborative planning phase	Uncertainty issues
Problem modelling	Uncertainty associated with modelling Uncertainty associated with the development of the model structure Uncertainty associated with the incorporation of important, but 'unknown' factors
Problem solving	Measurement theoretical debate Uncertainty associated with the used scale type Uncertainty associated with the response mode Uncertainty associated with vague judgements Uncertainty associated with incomplete pairwise comparison matrices Uncertainty associated with consistency measurement Uncertainty associated with priority derivation Uncertainty associated with the aggregation mode between the different levels of the problem modelling hierarchy Uncertainty associated with the type of sensitivity analysis

However, the review showed that many meta-choices have to be made to solve a decision problem, while the involved human judgements are subject to numerous cognitive and motivational biases (Ferretti & Montibeller, 2016; Montibeller & von Winterfeldt, 2015). This introduces another complexity layer, as the integration of uncertainty into the problem-solving process is itself a source of uncertainty. This is also true for the conducted critical literature review as meta-choices had to be made: The overview does not claim completeness; hence further developments could enlarge the scope of uncertainties considering aspects prior the actual application of the AHP as well. Additional uncertainty issues could be included (e.g., relating to the gathering of data and information (Beynon, 2002b; Beynon, Curry, &

Morgan, 2000), concerned about scenario planning (Durbach & Stewart, 2003; Stewart, French & Rios, 2013) or uncertainty issues associated with problem identification and structuring (Marttunen, Lienert, & Belton, 2017)) or related with widespread software implementations of the AHP, such as 'Expert Choice' (Ishizaka & Labib, 2009)) or a subtler differentiation within a single uncertainty issue could be elaborated.

As part of Publication II, a comprehensive uncertainty analysis has been developed to respond to RQ4 (How to systematically assess uncertainty referring to a specific decision-making case using the AHP?). This procedure is based on the three dimensions of uncertainty (Location, Level and Nature) proposed by Walker et al. (2003) and allows the analysis of the involved uncertainty regarding a specific sustainability problem embracing the designation, the categorization and the quantification of uncertainty. The comprehensive uncertainty analysis procedure is line with the suggestion that it is important to identify and describe uncertainties, to systematically consider and generate them within the models and to assess the uncertainty of the model output to improve the chance for a successful decision support system application (Walling & Vaneeckhaute, 2020). However, other authors developed a range of different overarching approaches to assess uncertainty (Jens Christian Refsgaard et al., 2007; Uusitalo et al., 2015).

The application of the developed comprehensive uncertainty analysis allows to respond to RQ5 (What is the numerical impact of uncertainty on the decision alternatives' priorities for different uncertainty scenarios?) and RQ6 (Does the consideration of uncertainty leads to rank reversals compared to the alternatives' ranking neglecting uncertainty for different uncertainty scenarios?). In particular, the computation of the simulation experiment using R (R Development Core Team, 2014) provided detailed answers as presented in Publication II. It showed that for the cases a rank reversal occurs, the absolute maximal impact caused by an US considering all alternatives is very small (approximately 0.03). Additionally, and with respect to a single USs and the specific case characteristics, a rank reversal occurs in about 50% of the simulated runs. Hence, from a theoretical normative point of view, the effects of considering uncertainty issues in the AHP methodology cannot satisfy the ideal of a rational decision analysis. From a descriptive point of view, considering the practice of decision makers, the absolute impacts of the considered uncertainties stay within reasonable limits, meaning that the maximal numerical impact stays on the hundredths decimal place. Here too, meta-choices had to be made. The algorithm for the quantification of the uncertainty issues related to the case study is based on several assumptions (e.g., usage of a specific set of input data or equal weights for single each family member). Each of these assumptions could be implemented differently (e.g., structures of randomly derived matrices may differ from structures of real-world matrices (Bozóki et al., 2013; Gass & Standard, 2002) or there could be reasons to give different weights to group members (Ishizaka & Nemery, 2013; Saaty & Peniwati, 2013). As the function PAM from the R-package 'cluster' is a more robust version of K-means (Rousseeuw, Struyf, & Hubert, 2014), three medoids for representing a sample of vectors within step (8) of the simulation experiment are feasible for the purpose of this study. However, the meta-choices and assumptions, i.e., which uncertainties should be included and in which way, narrowed and pre-determined to some extend the solution space of the simulation experiment.

5.3 Considering interactions of sustainability problems

As part of Publication III and providing answer to RQ7 (How can the ANP be applied to prioritize SDG targets?), the ANP as generalized form of the AHP has been applied to rank SDG targets considering all positive and possible indirect SDG target interactions in the evaluation at once. The data was input into the ANP model using the positive Nilsson scores of the cross-impact matrix (Weitz et al., 2018) using the direct data entry mode of Super Decisions v.3.2.0 (SuperDecisions, 2019a). The rationale behind applying the ANP is to allow the SDG target network to be represented as a graph and hence to permit all direct and indirect SDG target interactions to be considered. A limitation to this exists in that ANP mathematics relies on positive values only, which needs to exclude the negative SDG target interactions in an evaluation and hence neglect SDG target trade-offs. The ANP addresses many of the limitations of current approaches as listed by Ospina-Forero, Castañeda, & Guerrero (2020). It is easily scalable, i.e. enlargeable by additional factors, because it employs the software tool Super Decisions, an established and well-known product (SuperDecisions, 2019a). The replicability of the ANP application is given as the applied methods used for score elicitation as well as the subsequent steps to use this data to build an SDG target network are transparently and comprehensively described in the present study. The ANP model can be built for every region or country separately and thus allows a consideration of the socio-economic context in terms of their specific SDG target interactions. Additional contextual factors, such as good data availability are a prerequisite for the application of the ANP, which may not be given for countries in transition or countries of the global South. Additionally, the ANP allows a consideration of the directionality of the SDG target interactions, because its mathematics is based on graph theory. The validity of the ANP's mathematical foundation has been widely discussed in the literature and there is broad agreement about its' soundness in the scientific community (Whitaker, 2007a, 2007b).

Applying the multiple model uncertainty assessment approach and responding to RQ9 (Is the SDG target ranking sensitive to the applied analytical method?), Publication III shows that the ANP validates both re-calculated SDG target rankings initially based on the CI-matrix in terms of approving the best ranked SDG target, which indicates that these rankings are robust. Responding to RQ9, the consideration of third-order neighbours and beyond makes a difference for the ranks 4 to 5 of the presented top 5 ranked SDG targets (Table 17), as they are not identically ranked for both the re-calculated SDG target rankings and the ANP. Allen et al. (2019) report a high degree of consistency across the rankings they compared, in the sense of that seven of the top ten ranking targets were the same across the four different methods. However, the four methods lead to three different top ranked SDG targets. Another difference to the study presented here, and what is acknowledged by the authors, is, that they neglected a minority (12% negative interactions compared to the positive ones) of negative interactions applying network analysis methods. As there is no systematic comparison of 2nd order SDG target rankings with the n-order rankings as derived from the ANP, this result may not hold true in the context of other case studies. Important to note here, is the fact, that the priorities of the 3 top ranked SDG targets considering the synergistic potential (16.6, 8.4 and 12.1) (Table 16) are very similar, indicating that small uncertainties regarding the interaction scoring could change the best ranked SDG target. This procedure - applying several methodological approaches to a single country case study may contribute to overcoming the formulated impossibility of comprehensive validation tests for SDG target rankings (Ospina-Forero et al., 2020).

Publication III demonstrated how to use the ANP for prioritizing SDG targets in a multi-method setting embracing positive scores derived from the Nilsson-scale, the CI-matrix and network analysis. Responding to RQ10 (Does a multi-method application can provide better policy advice compared to a single method application?), the additional application of the ANP allowed to deepen the understanding how the overall quality of the policy advice can be improved. In particular, the computation of the n-order influence within an SDG target network allows to improve the information basis compared to the CI-matrix metrics. Network analysis application then complement the SDG target prioritization by providing advice for stakeholder prioritization and enhances the understanding of the system, which is targeted by SDG implementation action. Referring to the case study application, these simplified examples demonstrate that the combination of different analytical methods improves the overall quality of the formulated policy advice regarding its scope and methodological profoundness. However, the choice of the best suitable multi-method application referring to a specific case depends on various factors, such as the necessary sequence of analytical methods to come up with advice wanted and as well as on methodological properties as captured by the developed assessment criteria (Table 13).

Publication III additionally presented how methodological results derived could be framed as concrete policy advice to support its applicability for the policy process answering RQ11 (How can methodological results be translated into applicable policy advice?). This translation is based on the four basic types of advice that can be given to decision-makers: 'Recommend For', Recommend Against', 'Decision Support' and 'Information' (Dalal & Bonaccio, 2010). However, an empirical investigation which advice is better understood by policy makers and the exploration of reasons why a recommendation is finally utilized or discounted (Bonaccio & Dalal, 2006) has not been undertaken.

6 Conclusions

Collaborative planning is essential for a transition to a global SD path. Current collaborative planning activities in the context of SD focus on the implementation of the SDGs. The scientific community increasingly developed a broad variety of collaborative planning methods to foster the understanding of SDG entity interactions as basis for planning SDG implementation (Allen et al., 2021; Bennich et al., 2020; Miola et al., 2019). As a systematic evaluation of the applied methods properties is missing, this thesis has developed a set of criteria that was used to systematically assess 30 identified SDG entity interaction methods published from 2015 to the end of 2019 with respect to their methodological properties such as their ability to assess (i) effects between SDG entities, (ii) interdisciplinary sensitivity, (iii) to support collaboration and systems thinking and (iv) to their practicability of application. The evaluation results show, that some method categories (embracing multiple SDG entity interaction methods), such as Argumentative, Literature and Simulation, have the ability to give more detailed information on how SDG entities interact (e.g., direction of interaction, strength of interaction and positive/negative interaction) and thus are useful for creating an understanding of the dependencies given in the analyzed human-environment system. Other methods, belonging to the Statistical and Other quantitative methods category, have in contrast the simple benefit of being less time and resource intensive. Therefore, it will be important that decision analysts and consultants are aware about the characteristics of different collaborative planning methods and choose the right techniques in context of the socio-economic and ecological context of the sustainability problem.

Solving sustainability problems has to cope with a tremendous complexity arising from human-environment interaction. In particular, in the process of planning, important information may be lost, competing values may be discarded, and elements of uncertainty may be ignored. Hence, many decisions regarding SD bring along unintended consequences that are not reflected in the planning process (Dietz, 2003; Harding, Hendriks, & Faruqi, 2009; Kiker et al., 2005; Scholz & Binder, 2011). Therefore, authors argue for shedding light onto the systematic identification and consideration of different uncertainty issues within the process of solving sustainability problems as the understanding of the uncertainty's impact is crucial for the overall decision quality (Ascough Ii et al., 2008; Walling & Vaneeckhaute, 2020). In addition, the evaluation of the 30 identified SDG entity interaction methods showed that primarily the methods relating to the quantitative categories (Simulation, Other quantitative and Statistical) can develop a statement regarding the involved uncertainty's impact.

The AHP and ANP relate to the class of MCDM methods, which allow to model decision problems quantitatively. Two different overarching approaches to assess uncertainty involved in solving a sustainability problem were applied in this thesis. This was done by analyzing two sustainability problems in depth: 1) On the micro-level, a heating system purchase decision for a family house and 2) On the macro-level, an SDG target prioritization of the country case of Sweden. The first overarching approach to assess uncertainty was conducted by computing a comprehensive uncertainty analysis that studies the impact of different USs on the methodological result provided by the AHP. The second overarching approach assesses uncertainty by applying the ANP to the country case of Sweden to compare the results with results of other analytical methods. On the one hand, the rationale behind the multiple models' approach has been to assess if the SDG target ranking of the country case of Sweden is sensitive to the applied method. On the other hand, the analysis of the heating system purchase decision showed that the fundamental characteristics of this sustainability problem claim methodological extensions of the AHP. In particular, several uncertainty issues as firstly collected with the critical literature review are inherently rooted in the complex dependencies of linked human-environment systems as well as in the methodological properties of the applied method. The scope of the analysis allows drawing the conclusion that considering uncertainty in collaborative planning requires generally knowledge about the potential impact of uncertainties on the outcome. The application of the comprehensive uncertainty analysis developed in this thesis should constitute the basis of further action in related decision problems. Without this knowledge, there is a high chance that decision makers put more attention to specific uncertainty aspects, which might have at the end no effect on the final decision at all. As shown with the comprehensive uncertainty analysis there may be several cases where nearly equal shares of rank reversals for different uncertainty scenarios within a single variant occur. This indicates that from a practitioner's point of view, it is not obvious to which aspect of uncertainty more attention should be given.

A prioritization of SDG targets should ask for a method that considers all direct and indirect SDG target interactions to represent the SDG target network dynamics adequately. This thesis contributes to this methodological requirement with the first application of the ANP in order to consider all direct and indirect SDG target interactions at once. A limitation of the ANP application is related to its mathematics, which allows to consider positive values only, and needs to exclude negative SDG target interactions. This neglects possible SDG target trade-offs. Nevertheless, the ANP might be the right method choice for cases where the share of negative SDG target interactions is very small in relation to the positive SDG target interactions.

Many existing studies on SDG interactions have not bridged the gap of translating the methodological result into usable advice for problem solving (Breuer et al., 2019). Recent work highlighted that, the interpretation of the methodological results usually requires expert knowledge as the problem modelling assumptions, the uncertainty conditions and the potential uncertainty integration may be difficult to understand for the decision makers. In this context, the assessment of the 30 identified SDG entities interaction methods showed that mostly quantitative categories (Simulation, Other quantitative and Statistical) need specialized knowledge to interpret the methodological results. Hence, this thesis presented how methodological results derived from quantitative methods, such as the ANP, and concerning SDG prioritization, could be framed as concrete policy advice to support its applicability for the policy process based on the four basic types of advice that can be given to decision-makers (Dalal & Bonaccio, 2010) and therefore contributes to further close this research gap. If methodological uncertainty is addressed well, the likelihood that the advice will be taken up by decision makers can be increased (Brugnach et al., 2007; Gilbert et al., 2018). This thesis presented the application of the ANP as part of a multi-method setting to validate the SDG target rankings of other analytical methods (multiple models uncertainty assessment approach). Considering the validation results allows to improve the overall quality of the formulated policy and hence may increase its uptake by policy-makers.

This thesis put the analytic dimension of the methods used for prioritizing SDG targets for Sweden into the center and hence allow classifying the methods regarding their potential to formulate policy advice. It became evident that such a framing allows to guide the method choice with respect to different collaborative planning phases. For example, the Weitz et al. (2018) approach allows to enhance the system understanding in terms of identifying effective sub-networks of SDG targets which surely contributes to a better problem identification. Whereas the ANP shows a mathematical foundation that is best suited for problem solving. However, the systemic understanding of what it means to implement indivisibly connected SDGs in an interlinked human-environment system is still to be addressed by the scientific community as the potential of methods and tools to support this understanding is manifold.

The application of the ANP as part of a multi-method setting showed that a combination of different methods can improve the overall quality of the formulated policy advice regarding its scope and methodological profoundness. The integration of uncertainty whether originating from the characteristics of the sustainability problems or from the methodological properties of the applied method itself is a phenomenon that clearly needs more attention as it might act as game-changer. This indicates to elaborate an in-depth understanding of current methodological approaches to guide the choice toward the best multi-method application for approaching specific cases and specific collaborative planning phases as well as their related policy challenges and gaps concerned with SDG implementation (Allen, Metternicht, & Wiedmann, 2018; Bennich et al., 2020). However, to avoid 'paralysis by analysis', where the different methodological results remain unused, scientists will be required to develop new tools and methods that satisfy policymakers' needs (Allen et al., 2021; Lyytimäki et al., 2020). As sustainability problems are a representative of so-called wicked problems, it is necessary to plan in recurring cycles, because sustainability problems cannot be solved in a classical sense as they are resistant to a definite solution. The implemented solution will impact the interlinked human-environment system which then accordingly will change the definition of the problem (Eden & Wagstaff, 2020; Sediri et al., 2020). Several meta-choices, such as which uncertainty to include are involved in collaborative planning which itself can introduce uncertainty into problem solving. Hence, the identification of pros and cons of the identified methods can only be seen with respect to a specific aim of the method's application and its planning context. However, it can be concluded that actions implemented to support the transition to a global SD path have to go through the three phases of collaborative planning (problem identification, problem modelling, problem solving) repeatedly using multiple methods and or multi-method applications for different phases of collaborative planning.

7 References

Adams, W. J. L., & Saaty, R. (1999). SuperDecisions Software Guide. www.superdecisions.com.

Akinyemi, J. O., Solanke, B. L., & Odimegwu, C. O. (2018). Maternal employment and child survival during the era of sustainable development goals: Insights from proportional hazards modelling of Nigeria birth history data. Annals of global health, 84(1), 15-15.

Alcamo, J. (2019). Water quality and its interlinkages with the Sustainable Development Goals. Current Opinion in Environmental Sustainability, 36, 126-140. doi:https://doi.org/10.1016/j.cosust.2018.11.005

Alcamo, J., Thompson, J., Alexander, A., Antoniades, A., Delabre, I., Dolley, J., . . . Scharlemann, J. P. W. (2020). Analysing interactions among the sustainable development goals: findings and emerging issues from local and global studies. Sustainability Science, 15(6), 1561-1572. doi:10.1007/s11625-020-00875-x

Allen, C., Metternicht, G., & Wiedmann, T. (2018). Initial progress in implementing the Sustainable Development Goals (SDGs): a review of evidence from countries. Sustainability Science. doi:10.1007/s11625-018-0572-3

Allen, C., Metternicht, G., & Wiedmann, T. (2019). Prioritising SDG targets: assessing baselines, gaps and interlinkages. Sustainability Science, 14(2), 421-438. doi:10.1007/s11625-018-0596-8

Allen, C., Metternicht, G., & Wiedmann, T. (2021). Priorities for science to support national implementation of the sustainable development goals: A review of progress and gaps. Sustainable Development, n/a(n/a), 1-18. doi:https://doi.org/10.1002/sd.2164

Allen, C., Metternicht, G., Wiedmann, T., & Pedercini, M. (2019). Greater gains for Australia by tackling all SDGs but the last steps will be the most challenging. Nature Sustainability, 2(11), 1041-1050. doi:10.1038/s41893-019-0409-9

Altuzarra, A., Moreno-Jiménez, J. M., & Salvador, M. (2007). A Bayesian priorization procedure for AHP-group decision making. European Journal of Operational Research, 182(1), 367-382. doi:http://dx.doi.org/10.1016/j.ejor.2006.07.025

Ascough Ii, J., Maier, H. R., Ravalico, J. K., & Strudley, M. (2008). Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecological modelling, 219(3), 383-399.

Assuad, C. S. A. (2020). Understanding Rationality in Sustainable Development Decision-Making: Unfolding the Motivations for Action. Journal of the Knowledge Economy, 11(3), 1086-1119. doi:10.1007/s13132-019-0585-x

Aull-Hyde, R., Erdogan, S., & Duke, J. M. (2006). An experiment on the consistency of aggregated comparison matrices in AHP. European Journal of Operational Research, 171(1), 290-295.

Bana e Costa, C. A., & Vansnick, J.-C. (2008). A critical analysis of the eigenvalue method used to derive priorities in AHP. European Journal of Operational Research, 187(3), 1422-1428. doi:http://dx.doi.org/10.1016/j.ejor.2006.09.022

Banerjee, O., Cicowiez, M., Horridge, M., & Vargas, R. (2019). Evaluating synergies and trade-offs in achieving the SDGs of zero hunger and clean water and sanitation: An application of the IEEM Platform to Guatemala. Ecological Economics, 161, 280-291. doi:https://doi.org/10.1016/j.ecolecon.2019.04.003

Bangert, M., Molyneux, D. H., Lindsay, S. W., Fitzpatrick, C., & Engels, D. (2017). The cross-cutting contribution of the end of neglected tropical diseases to the sustainable development goals. Infectious diseases of poverty, 6(1), 1-20.

Barzilai, J. (2001). Notes on the Analytic Hierarchy Process. Paper presented at the NSF Design and Manufacturing Research Conference, Tampa, Florida.

Barzilai, J. (2006). On the mathematical modelling of measurement. Retrieved from http://arxiv.org/ftp/math/papers/0609/0609555.pdf:

Barzilai, J., & Golany, B. (1994). AHP rank reversal, normalization and aggregation rules. INFOR, 32(2).

Belton, V., & Gear, A. (1985). The legitimacy of rank reversal - a comment. Omega, 13, 143-144.

Belton, V., & Gear, T. (1983). On a short-coming of Saaty's method of analytic hierarchies. Omega, 11(3), 228-230. doi:http://dx.doi.org/10.1016/0305-0483(83)90047-6

Belton, V., & Stewart, T. J. (2002). Multiple Criteria Decision Analysis: An Integrated Approach: Kluwer Academic Publishers.

Bennich, T., Weitz, N., & Carlsen, H. (2020). Deciphering the scientific literature on SDG interactions: A review and reading guide. Science of The Total Environment, 728, 138405. doi:https://doi.org/10.1016/j.scitotenv.2020.138405

Bernasconi, M., Choirat, C., & Seri, R. (2010). The Analytic Hierarchy Process and the theory of measurement. Management Science, 56, 699-711.

Bernasconi, M., Choirat, C., & Seri, R. (2011). A re-examination of the algebraic properties of the AHP as a ratio-scaling technique. Journal of Mathematical Psychology, 55(2), 152-165. doi:http://dx.doi.org/10.1016/j.jmp.2010.11.002

Beynon, M. (2002a). An analysis of distributions of priority values from alternative comparison scales within AHP. European Journal of Operational Research, 140(1), 104-117. doi:http://dx.doi.org/10.1016/S0377-2217(01)00221-1

Beynon, M. (2002b). DS/AHP method: A mathematical analysis, including an understanding of uncertainty. European Journal of Operational Research, 140(1), 148-164. doi:http://dx.doi.org/10.1016/S0377-2217(01)00230-2

Beynon, M., Curry, B., & Morgan, P. (2000). The Dempster–Shafer theory of evidence: an alternative approach to multicriteria decision modelling. Omega, 28(1), 37-50. doi:http://dx.doi.org/10.1016/S0305-0483(99)00033-X

Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., . . . others. (2016). Achieving sustainable development goals from a water perspective. Frontiers in Environmental Science, 4, 64-64.

Biermann, F., Kanie, N., & Kim, R. E. (2017). Global governance by goal-setting: the novel approach of the UN Sustainable Development Goals. Current Opinion in Environmental Sustainability, 26-27, 26-31. doi:https://doi.org/10.1016/j.cosust.2017.01.010

Blicharska, M., Smithers, R. J., Mikusiński, G., Rönnbäck, P., Harrison, P. A., Nilsson, M., & Sutherland, W. J. (2019). Biodiversity's contributions to sustainable development. Nature Sustainability, 2(12), 1083-1093. doi:10.1038/s41893-019-0417-9

Bonaccio, S., & Dalal, R. S. (2006). Advice taking and decision-making: An integrative literature review, and implications for the organizational sciences. Organizational Behavior and Human Decision Processes, 101(2), 127-151. doi:https://doi.org/10.1016/j.obhdp.2006.07.001

Bowen, K. J., Cradock-Henry, N. A., Koch, F., Patterson, J., Häyhä, T., Vogt, J., & Barbi, F. (2017). Implementing the "Sustainable Development Goals": towards addressing three key governance challenges—collective action, trade-offs, and accountability. Current Opinion in Environmental Sustainability, 26-27, 90-96. doi:https://doi.org/10.1016/j.cosust.2017.05.002

Bozóki, S., & Rapcsák, T. (2008). On Saaty's and Koczkodaj's inconsistencies of pairwise comparison matrices. Journal of Global Optimization, 42(2), 157-175.

Bozóki, S., Dezső, L., Poesz, A., & Temesi, J. (2013). Analysis of pairwise comparison matrices: an empirical research. Annals of Operations Research, 211(1), 511-528. doi:10.1007/s10479-013-1328-1

Bozóki, S., Fülöp, J., & Rónyai, L. (2010). On optimal completion of incomplete pairwise comparison matrices. Mathematical and Computer Modelling, 52(1–2), 318-333. doi:http://dx.doi.org/10.1016/j.mcm.2010.02.047

Bozóki, S., Fülöp, J., & Rónyai, L. (2010). On optimal completion of incomplete pairwise comparison matrices. Mathematical and Computer Modelling, 52(1–2), 318-333. doi:http://dx.doi.org/10.1016/j.mcm.2010.02.047

Brandi, C. (2015). Safeguarding the earth system as a priority for sustainable development and global ethics: the need for an earth system SDG. Journal of Global Ethics, 11(1), 32-36. doi:10.1080/17449626.2015.1006791

Brecha, R. J. (2019). Threshold electricity consumption enables multiple sustainable development goals. Sustainability, 11(18), 5047-5047.

Breuer, A., Janetschek, H., & Malerba, D. (2019). Translating Sustainable Development Goal (SDG) Interdependencies into Policy Advice. Sustainability, 11(7), 2092.

Bringezu, S. (2018). Key strategies to achieve the SDGs and consequences for monitoring resource use. In H. Stephan & A. Reza (Eds.), Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals (pp. 11-34): Springer.

Brugha, C. (1998). Structuring and Weighting Criteria in Multi Criteria Decision Making (MCDM). Paper presented at the Trends in Multicriteria Decision Making: Proceedings of the 13th International Conference on Multiple Criteria Decision Making.

Brugha, C. (1998). Structuring and Weighting Criteria in Multi Criteria Decision Making (MCDM). Paper presented at the Trends in Multicriteria Decision Making: Proceedings of the 13th International Conference on Multiple Criteria Decision Making.

Brugha, C. M. (2004). Structure of multi-criteria decision-making. The Journal of the Operational Research Society, 55(11), 1156-1168.

Brugnach, M., Tagg, A., Keil, F., & de Lange, W. J. (2007). Uncertainty Matters: Computer Models at the Science–Policy Interface. Water Resources Management, 21(7), 1075-1090. doi:10.1007/s11269-006-9099-y

Buonocore, J. J., Choma, E., Villavicencio, A. H., Spengler, J. D., Koehler, D. A., Evans, J. S., . . . Sanchez-Pina, R. (2019). Metrics for the sustainable development goals: renewable energy and transportation. Palgrave Communications, 5(1), 136. doi:10.1057/s41599-019-0336-4

Butler, J., Jia, J., & Dyer, J. (1997). Simulation techniques for the sensitivity analysis of multi-criteria decision models. European Journal of Operational Research, 103(3), 531-546. doi:http://dx.doi.org/10.1016/S0377-2217(96)00307-4

Campagnolo, L., & Davide, M. (2019). Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality. World Development, 122, 96-109.

Cao, D., Leung, L. C., & Law, J. S. (2008). Modifying inconsistent comparison matrix in analytic hierarchy process: A heuristic approach. Decision Support Systems, 44(4), 944-953. doi:10.1016/j.dss.2007.11.002

Carmone Jr, F. J., Kara, A., & Zanakis, S. H. (1997). A Monte Carlo investigation of incomplete pairwise comparison matrices in AHP. European Journal of Operational Research, 102(3), 538-553. doi:http://dx.doi.org/10.1016/S0377-2217(96)00250-0

Cerveny, M., & Sturm, T. (2012). Lebenszykluskosten neuer Heizsystemen für alte Einfamilienhäuser - Vergleich der Lebenszykluskosten von Heizöl-, Erdgas-, Pellet- und Scheitholzheizungen für Einfamilienhäuser in drei (+ neun) Szenarien. Retrieved from

Chen, H., & Kocaoglu, D. F. (2008). A sensitivity analysis algorithm for hierarchical decision models. European Journal of Operational Research, 185(1), 266-288. doi:http://dx.doi.org/10.1016/j.ejor.2006.12.029

Choo, E. U., & Wedley, W. C. (2004). A common framework for deriving preference values from pairwise comparison matrices. Computers & Operations Research, 31(6), 893-908. doi:http://dx.doi.org/10.1016/S0305-0548(03)00042-X

Choo, E. U., & Wedley, W. C. (2010). Estimating ratio scale values when units are unspecified. Computers & Industrial Engineering, 59(2), 200-208. doi:http://dx.doi.org/10.1016/j.cie.2010.04.001

Choo, E. U., Schoner, B., & Wedley, W. C. (1999). Interpretation of criteria weights in multicriteria decision making. Computers & Industrial Engineering, 37(3), 527-541. doi:http://dx.doi.org/10.1016/S0360-8352(00)00019-X

Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecological Indicators, 46, 138-148. doi:http://dx.doi.org/10.1016/j.ecolind.2014.06.011

Cinelli, M., Kadziński, M., Gonzalez, M., & Słowiński, R. (2020). How to support the application of multiple criteria decision analysis? Let us start with a comprehensive taxonomy. Omega, 96, 102261. doi:https://doi.org/10.1016/j.omega.2020.102261

Cluver, L. D., Orkin, F. M., Meinck, F., Boyes, M. E., Yakubovich, A. R., & Sherr, L. (2016). Can social protection improve sustainable development goals for adolescent health? PLoS one, 11(10), e0164808-e0164808.

Collste, D., Pedercini, M., & Cornell, S. E. (2017). Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. Sustainability Science, 12(6), 921-931. doi:10.1007/s11625-017-0457-x

Dadkhah, K. M., & Zahedi, F. (1993). A mathematical treatment of inconsistency in the analytic hierarchy process. Mathematical and Computer Modelling, 17(4–5), 111-122. doi:http://dx.doi.org/10.1016/0895-7177(93)90180-7

Dalal, R. S., & Bonaccio, S. (2010). What types of advice do decision-makers prefer? Organizational Behavior and Human Decision Processes, 112(1), 11-23. doi:https://doi.org/10.1016/j.obhdp.2009.11.007

Davide, M., De Cian, E., & Bernigaud, A. (2019). Building a Framework to Understand the Energy Needs of Adaptation. Sustainability, 11(15). doi:10.3390/su11154085

Dawes, J. H. P. (2020). Are the Sustainable Development Goals self-consistent and mutually achievable? Sustainable Development, 28(1), 101-117. doi:https://doi.org/10.1002/sd.1975

De Paiva Serôa Da Motta, R., 2019. The sustainable development goals and 1.5° C climate change. World Review of Science, Technology and Sustainable Development 15, 123–144.

Deng, H. (1999). Multicriteria analysis with fuzzy pairwise comparison. International Journal of Approximate Reasoning, 21(3), 215-231. doi:http://dx.doi.org/10.1016/S0888-613X(99)00025-0

Deparis, S., Mousseau, V., Öztürk, M., Pallier, C., & Huron, C. (2012). When conflict induces the expression of incomplete preferences. European Journal of Operational Research, 221(3), 593-602.

Dietz, T. (2003). What is a Good Decision? Criteria for Environmental Decision Making. Human Ecology Review, 10(1).
Dittrich, R., Francis, B., Hatzinger, R., & Katzenbeisser, W. (2012). Missing observations in paired comparison data. Statistical Modelling, 12(2), 117-143.
Dodd, F. J., Donegan, H. A., & McMaster, T. B. M. (1993). A statistical approach to consistency in AHP. Mathematical and Computer Modelling, 18(6), 19-22. doi:http://dx.doi.org/10.1016/0895-7177(93)90123-G
Doelman, J. C., Stehfest, E., Tabeau, A., & van Meijl, H. (2019). Making the Paris agreement climate targets consistent with food security objectives. Global Food Security, 23, 93-103. doi:https://doi.org/10.1016/j.gfs.2019.04.003
Donaires, O. S., Cezarino, L. O., Caldana, A. C. F., & Liboni, L. (2019). Sustainable development goals – an analysis of outcomes. Kybernetes, 48(1), 183-207. doi:10.1108/K-10-2017-0401
Donegan, H. A., & Dodd, F. J. (1991). A note on saaty's random indexes. Mathematical and Computer Modelling, 15(10), 135-137. doi:http://dx.doi.org/10.1016/0895-7177(91)90098-R
Dong, Y., Hong, W.-C., Xu, Y., & Yu, S. (2013). Numerical scales generated individually for analytic hierarchy process. European Journal of Operational Research, 229(3), 654-662. doi:http://dx.doi.org/10.1016/j.ejor.2013.03.019
Dong, Y., Xu, Y., Li, H., & Dai, M. (2008). A comparative study of the numerical scales and the prioritization methods in AHP. European Journal of Operational Research, 186(1), 229-242.
Dong, Y., Zhang, G., Hong, W.-C., & Xu, Y. (2010). Consensus models for AHP group decision making under row geometric mean prioritization method. Decision Support Systems, 49(3), 281-289. doi:http://dx.doi.org/10.1016/j.dss.2010.03.003
Dörgő, G., Sebestyén, V., & Abonyi, J. (2018). Evaluating the Interconnectedness of the Sustainable Development Goals Based on the Causality Analysis of Sustainability Indicators. Sustainability, 10(10). doi:10.3390/su10103766
Dos Santos, P. H., Neves, S. M., Sant’Anna, D. O., Oliveira, C. H. d., & Carvalho, H. D. (2019). The analytic hierarchy process supporting decision making for sustainable development: An overview of applications. Journal of Cleaner Production, 212, 119-138. doi:https://doi.org/10.1016/j.jclepro.2018.11.270
Dovers, S. (2005). Environment and Sustainability Policy: Creation, Implementation, Evaluation: Federation Press.
Durbach, I. N., & Stewart, T. J. (2012). Modeling uncertainty in multi-criteria decision analysis. European Journal of Operational Research, 223(1), 1-14. doi:http://dx.doi.org/10.1016/j.ejor.2012.04.038
Durbach, I., & Stewart, T. J. (2003). Integrating scenario planning and goal programming. Journal of Multi-Criteria Decision Analysis 12(4-5), 261-271.
Dyer, J. S. (1990). Remarks on the Analytic Hierarchy Process. Management Science, 36(3), 249-258.
E-Control. (2004). Wie hoch ist mein durchschnittlicher Gasverbrauch? Retrieved from http://www.e-control.at/portal/page/portal/medienbibliothek/gas/dokumente/pdfs/durchsch-gasverbrauch.pdf:
Eden, L., & Wagstaff, M. F. (2020). Evidence-based policymaking and the wicked problem of SDG 5 Gender Equality. Journal of International Business Policy. doi:10.1057/s42214-020-00054-w

Eisenmenger, N., Pichler, M., Krenmayr, N., Noll, D., Plank, B., Schalmann, E., . . . Gingrich, S. (2020). The Sustainable Development Goals prioritize economic growth over sustainable resource use: a critical reflection on the SDGs from a socio-ecological perspective. Sustainability Science, 15(4), 1101-1110. doi:10.1007/s11625-020-00813-x

Engström, R. E., Destouni, G., Howells, M., Ramaswamy, V., Rogner, H., & Bazilian, M. (2019). Cross-Scale Water and Land Impacts of Local Climate and Energy Policy—A Local Swedish Analysis of Selected SDG Interactions. Sustainability, 11(7). doi:10.3390/su11071847

Engström, R. E., Howells, M., & Destouni, G. (2018). Water impacts and water-climate goal conflicts of local energy choices--notes from a Swedish perspective. Proceedings of the International Association of Hydrological Sciences, 376, 25-33.

Fader, M., Cranmer, C., Lawford, R., & Engel-Cox, J. (2018). Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets. Frontiers in Environmental Science, 6(112). doi:10.3389/fenvs.2018.00112

Federal Environment Agency, A. (2001). Sechster Umweltkontrollbericht. Retrieved from

Fedrizzi, M., & Giove, S. (2007). Incomplete pairwise comparison and consistency optimization. European Journal of Operational Research, 183(1), 303-313. doi:http://dx.doi.org/10.1016/j.ejor.2006.09.065

Feng, T.-t., Kang, Q., Pan, B.-b., & Yang, Y.-s. (2019). Synergies of sustainable development goals between China and countries along the Belt and Road initiative. Current Opinion in Environmental Sustainability, 39, 167-186. doi:https://doi.org/10.1016/j.cosust.2019.10.008

Ferretti, V., & Montibeller, G. (2016). Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems. Decision Support Systems, 84, 41-52. doi:http://dx.doi.org/10.1016/j.dss.2016.01.005

Finan, J. S., & Hurley, W. J. (1999). Transitive calibration of the AHP verbal scale. European Journal of Operational Research, 112(2), 367-372. doi:http://dx.doi.org/10.1016/S0377-2217(97)00411-6

Finan, J. S., & Hurley, W. J. (2002). The analytic hierarchy process: can wash criteria be ignored? Computers & Operations Research, 29(8), 1025-1030.

Fisher, J. E., Andersen, Z. J., Loft, S., & Pedersen, M. (2017). Opportunities and challenges within urban health and sustainable development. Current Opinion in Environmental Sustainability, 25, 77-83.

Forman, E., & Peniwati, K. (1998). Aggregating individual judgments and priorities with the analytic hierarchy process. European Journal of Operational Research, 108(1), 165-169. doi:http://dx.doi.org/10.1016/S0377-2217(97)00244-0

Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B. L., . . . van Vuuren, D. (2019). A multi-model assessment of food security implications of climate change mitigation. Nature Sustainability, 2(5), 386-396. doi:10.1038/s41893-019-0286-2

Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., . . . Milligan, B. (2019). Connecting climate action with other Sustainable Development Goals. Nature Sustainability, 2(8), 674-680. doi:10.1038/s41893-019-0334-y

Gabbert, S., Van Ittersum, M., Kroeze, C., Stalpers, S., Ewert, F., Olsson, J.A., 2010. Uncertainty analysis in integrated assessment: the users' perspective. Regional Environmental Change 10, 131–143.

Gao, L., & Bryan, B. A. (2017). Finding pathways to national-scale land-sector sustainability. Nature, 544(7649), 217-222.

Gass, S. I., & Standard, S. M. (2002). Characteristics of Positive Reciprocal Matrices in the Analytic Hierarchy Process. The Journal of the Operational Research Society, 53(12), 1385-1389. doi:10.2307/822729

Gilbert, N., Ahrweiler, P., Barbrook-Johnson, P., Narasimhan, K. P., & Wilkinson, H. (2018). Computational Modelling of Public Policy: Reflections on Practice. Journal of Artificial Societies and Social Simulation, 21(1), 14. doi:10.18564/jasss.3669

Grošelj, P., & Stirn, L. Z. (2012). Acceptable consistency of aggregated comparison matrices in analytic hierarchy process. European Journal of Operational Research, 223(2), 417-420.

Grošelj, P., Zadnik Stirn, L., Ayrilmis, N., & Kuzman, M. K. (2015). Comparison of some aggregation techniques using group analytic hierarchy process. Expert Systems with Applications, 42(4), 2198-2204. doi:http://dx.doi.org/10.1016/j.eswa.2014.09.060

Haines, A., Amann, M., Borgford-Parnell, N., Leonard, S., Kuylenstierna, J., & Shindell, D. (2017). Short-lived climate pollutant mitigation and the Sustainable Development Goals. Nature Climate Change, 7(12), 863-869.

Hall, N. L., Ross, H., Richards, R., Barrington, D. J., Dean, A. J., Head, B. W., . . . Hill, P. S. (2018). Implementing the United Nations' sustainable development goals for water and beyond in Australia: A proposed systems approach. Australasian journal of water resources, 22(1), 29-38.

Hall, R. P., Ranganathan, S., & Gc, R. K. (2017). A general micro-level modeling approach to analyzing interconnected SDGs: Achieving SDG 6 and more through multiple-use water services (MUS). Sustainability, 9(2), 314-314.

Hämäläinen, R. P. (2015). Behavioural issues in environmental modelling – The missing perspective. Environmental Modelling & Software, 73, 244-253. doi:http://dx.doi.org/10.1016/j.envsoft.2015.08.019

Hanjra, M. A., Noble, A., Langan, S., & Lautze, J. (2016). Feeding the 10 billion within the sustainable development goals framework. In I. J. Gordon, H. H. T. Prins, & G. R. Squire (Eds.), Food Production and Nature Conservation (pp. 35-60): Routledge.

Harding, R., Hendriks, C. M., & Faruqi, M. (2009). Environmental decision-making: exploring complexity and context: Federation Press.

Harker, P. T. (1987a). Alternative modes of questioning in the analytic hierarchy process. Mathematical Modelling, 9(3–5), 353-360. doi:http://dx.doi.org/10.1016/0270-0255(87)90492-1

Harker, P. T. (1987b). Incomplete pairwise comparisons in the analytic hierarchy process. Mathematical Modelling, 9(11), 837-848. doi:http://dx.doi.org/10.1016/0270-0255(87)90503-3

Harker, P. T., & Vargas, L. G. (1990). Reply to "Remarks on the Analytic Hierarchy Process" by J. S. Dyer. Management Science, 36(3), 269-273.

Hazarika, R., & Jandl, R. (2019). The Nexus between the Austrian Forestry Sector and the Sustainable Development Goals: A Review of the Interlinkages. Forests, 10(3). doi:10.3390/f10030205

Heck, V., Hoff, H., Wirsenius, S., Meyer, C., & Kreft, H. (2018). Land use options for staying within the Planetary Boundaries--Synergies and trade-offs between global and local sustainability goals. Global environmental change, 49, 73-84.

Hepp, P., Somerville, C., & Borisch, B. (2019). Accelerating the United Nation's 2030 Global Agenda: Why Prioritization of the Gender Goal is Essential. Global Policy, 10(4), 677-685. doi:https://doi.org/10.1111/1758-5899.12721

Herman, M. W., & Koczkodaj, W. W. (1996). A Monte Carlo study of pairwise comparison. Information Processing Letters, 57(1), 25-29. doi:http://dx.doi.org/10.1016/0020-0190(95)00185-9

Hofmann, K. P. (Ed.) (2007). Psychology of Decision Making in Economics, Business and Finance.

Holder, R. D. (1990). Some Comments on the Analytic Hierarchy Process. The Journal of Operational Research Society, 41(11), 1073-1076.

Howden-Chapman, P., Keall, M., Whitwell, K., & Chapman, R. (2020). Evaluating natural experiments to measure the co-benefits of urban policy interventions to reduce carbon emissions in New Zealand. Science of the Total Environment, 700, 134408-134408.

Hua, Z., Gong, B., & Xu, X. (2008). A DS–AHP approach for multi-attribute decision making problem with incomplete information. Expert Systems with Applications, 34(3), 2221-2227. doi:http://dx.doi.org/10.1016/j.eswa.2007.02.021

Hubacek, K., Baiocchi, G., Feng, K., & Patwardhan, A. (2017). Poverty eradication in a carbon constrained world. Nature communications, 8(1), 1-9.

Huber, H., Schöfmann, P., & Zottl, A. (2014). Wärme! pumpen - zur energieeffizienten Wärmeversorgung - Technologieleitfaden Wärmepumpen. Retrieved from http://www.wien.gv.at/stadtentwicklung/energieplanung/pdf/waermepumpenleitfaden.pdf

Huizingh, E. K. R. E., & Vrolijk, H. C. J. (1997). A Comparison of Verbal and Numerical Judgments in the Analytic Hierarchy Process. Organizational Behavior and Human Decision Processes, 70(3), 237-247. doi:http://dx.doi.org/10.1006/obhd.1997.2708

Hung, M.-L., Ma, H.-W., & Yang, W.-F. (2009). Uncertainty Analysis of the Analytic Hierarchy Process methodology. J. Environ. Eng. Manage., 19(3), 145-154.

Huo, L.-a., Lan, J., & Wang, Z. (2011). New parametric prioritization methods for an analytical hierarchy process based on a pairwise comparison matrix. Mathematical and Computer Modelling, 54(11–12), 2736-2749. doi:http://dx.doi.org/10.1016/j.mcm.2011.06.062

Hutton, C. W., Nicholls, R. J., Lázár, A. N., Chapman, A., Schaafsma, M., & Salehin, M. (2018). Potential trade-offs between the sustainable development goals in coastal Bangladesh. Sustainability, 10(4), 1108-1108.

Ishizaka, A., & Labib, A. (2009). Analytic Hierarchy Process and Expert Choice: Benefits and Limitations. OR Insight, 22(4), 201-220.

Ishizaka, A., & Labib, A. (2011a). Review of the main developments in the analytic hierarchy process. Expert Systems with Applications, 38(11), 14336-14345. doi:http://dx.doi.org/10.1016/j.eswa.2011.04.143

Ishizaka, A., & Labib, A. (2011b). Selection of new production facilities with the Group Analytic Hierarchy Process Ordering method. Expert Systems with Applications, 38(6), 7317-7325. doi:http://dx.doi.org/10.1016/j.eswa.2010.12.004

Ishizaka, A., & Lusti, M. (2004). An expert module to improve the consistency of AHP matrices. International Transactions in operational research, 11, 97-105.

Ishizaka, A., & Lusti, M. (2006). How to derive priorities in AHP: A comparative study. Central European Journal of Operations Research, 14(4), 387-400.

Ishizaka, A., & Nemery, P. (2013). Multi-criteria Decision Analysis: Methods and Software: Wiley.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software 21, 602–614.

Jaramillo, F., Desormeaux, A., Hedlund, J., Jawitz, J. W., Clerici, N., Piemontese, L., . . . Åhlén, I. (2019). Priorities and Interactions of Sustainable Development Goals (SDGs) with Focus on Wetlands. Water, 11(3). doi:10.3390/w11030619

Jiménez-Aceituno, A., Peterson, G. D., Norström, A. V., Wong, G. Y., & Downing, A. S. (2020). Local lens for SDG implementation: lessons from bottom-up approaches in Africa. Sustainability Science, 15(3), 729-743. doi:10.1007/s11625-019-00746-0

Johnson, C. R., Beine, W. B., & Wang, T. J. (1979). Right-left asymmetry in an eigenvector ranking procedure. Journal of Mathematical Psychology, 19(1), 61-64.

Kandakoglu, A., Frini, A., & Ben Amor, S. (2019). Multicriteria decision making for sustainable development: A systematic review. Journal of Multi-Criteria Decision Analysis, 26(5-6), 202-251. doi:10.1002/mcda.1682

Kanie, N., Griggs, D., Young, O., Waddell, S., Shrivastava, P., Haas, P. M., . . . Kőrösi, C. (2019). Rules to goals: emergence of new governance strategies for sustainable development. Sustainability Science, 14(6), 1745-1749. doi:10.1007/s11625-019-00729-1

Karapetrovic, S., & Rosenbloom, E. S. (1999). A quality control approach to consistency paradoxes in AHP. European Journal of Operational Research, 119(3), 704-718. doi:http://dx.doi.org/10.1016/S0377-2217(98)00334-8

Kheybari, S., Rezaie, F. M., & Farazmand, H. (2020). Analytic network process: An overview of applications. Applied Mathematics and Computation, 367, 124780. doi:https://doi.org/10.1016/j.amc.2019.124780

Kiker, G. A., Bridges, T. S., Varghese, A., Seager, T. P., & Linkov, I. (2005). Application of multicriteria decision analysis in environmental decision making. Integrated Environmental Assessment and Management, 1(2), 95-108. doi:10.1897/IEAM_2004a-015.1

Kirchner, M., Mitter, H., Schneider, U. A., Sommer, M., Falkner, K., & Schmid, E. (2021). Uncertainty concepts for integrated modeling - Review and application for identifying uncertainties and uncertainty propagation pathways. Environmental Modelling & Software, 135, 104905. doi:https://doi.org/10.1016/j.envsoft.2020.104905

Klauer, B., Manstetten, R., Petersen, T., & Schiller, J. (2013). The art of long-term thinking: A bridge between sustainability science and politics. Ecological Economics, 93, 79-84. doi:https://doi.org/10.1016/j.ecolecon.2013.04.018

Kroll, C., Warchold, A., & Pradhan, P. (2019). Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies? Palgrave Communications, 5(1), 140. doi:10.1057/s41599-019-0335-5

Kumar, P., Ahmed, F., Singh, R. K., & Sinha, P. (2018). Determination of hierarchical relationships among sustainable development goals using interpretive structural modeling. Environment, Development and Sustainability, 20(5), 2119-2137. doi:10.1007/s10668-017-9981-1

Kunčič, A. (2019). Prioritising the Sustainable Development Goals using a network approach: SDG linkages and groups. Theorija in praksa, 56, 418-437.

Kwiesielewicz, M., & Van Uden, E. (2003). Ranking decision variants by subjective paired comparisons in cases with incomplete data. Paper presented at the Proceedings of the 2003 international conference on Computational science and its applications: PartIII, Montreal, Canada.

Kwiesielewicz, M., & van Uden, E. (2004). Inconsistent and contradictory judgements in pairwise comparison method in the AHP. Computers & Operations Research, 31(5), 713-719. doi:http://dx.doi.org/10.1016/S0305-0548(03)00022-4

Lamata, M. T., & Alonso, J. A. (2006). Consistency in the Analytic Hierarchy Process: a new approach. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 14(04), 445-459. doi:doi:10.1142/S0218488506004114

Le Blanc, D. (2015). Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. Sustainable Development, 23(3), 176-187. doi:doi:10.1002/sd.1582

Leskinen, P. (2001). Measurement scales and interval judgements in the AHP. Paper presented at the ISAHP, Berne, Switzerland.

Leung, L. C., & Cao, D. (2000). On consistency and ranking of alternatives in fuzzy AHP. European Journal of Operational Research, 124(1), 102-113. doi:http://dx.doi.org/10.1016/S0377-2217(99)00118-6

Levary, R. R., & Wan, K. (1998). A simulation approach for handling uncertainty in the analytic hierarchy process. European Journal of Operational Research, 106(1), 116-122. doi:http://dx.doi.org/10.1016/S0377-2217(97)00134-3

Liang, L., Wang, G., Hua, Z., & Zhang, B. (2008). Mapping verbal responses to numerical scales in the analytic hierarchy process. Socio-Economic Planning Sciences, 42(1), 46-55. doi:http://dx.doi.org/10.1016/j.seps.2005.10.006

Lim, M. M. L., Jørgensen, P. S., & Wyborn, C. A. (2018). Reframing the sustainable development goals to achieve sustainable development in the Anthropocene—a systems approach. Ecology and Society, 23(3).

Lu, Y., Nakicenovic, N., Visbeck, M., & Stevance, A.-S. (2015). Policy: Five priorities for the UN Sustainable Development Goals. Nature, 520(7548), 432-433. doi:10.1038/520432a

Lucas, P. L., Hilderink, H. B. M., Janssen, P. H. M., Kc, S., van Vuuren, D. P., & Niessen, L. (2019). Future impacts of environmental factors on achieving the SDG target on child mortality—A synergistic assessment. Global Environmental Change, 57, 101925. doi:https://doi.org/10.1016/j.gloenvcha.2019.05.009

Lusseau, D., & Mancini, F. (2019). Income-based variation in Sustainable Development Goal interaction networks. Nature Sustainability, 2(3), 242-247. doi:10.1038/s41893-019-0231-4

Lyytimäki, J., Lonkila, K.-M., Furman, E., Korhonen-Kurki, K., & Lähteenoja, S. (2020). Untangling the interactions of sustainability targets: synergies and trade-offs in the Northern European context. Environment, Development and Sustainability. doi:10.1007/s10668-020-00726-w

Maier, H. R., Ascough, J. C., Wattenbach, M., Renschler, C. S., & Labiosa, W. B. (2008). Uncertainty in Environmental Decision Making: Issues, Challenges and Future Directions. In A. J. Jakeman, A. A. Voinov, A. E. Rizzoli, & S. H. Chen (Eds.), Environmental Modelling, Software and Decision Support: State of the art and new perspective: Elsevier Science.

Mainali, B., Luukkanen, J., Silveira, S., & Kaivo-Oja, J. (2018). Evaluating synergies and trade-offs among sustainable development goals (SDGs): explorative analyses of development paths in South Asia and sub-Saharan Africa. Sustainability, 10(3), 815-815.

Maleki, H., & Zahir, S. (2013). A Comprehensive Literature Review of the Rank Reversal Phenomenon in the Analytic Hierarchy Process. Journal of Multi-Criteria Decision Analysis, 20(3-4), 141-155. doi:10.1002/mcda.1479

Malerba, D. (2019). Poverty-energy-emissions pathways: Recent trends and future sustainable development goals. Energy for Sustainable Development, 49, 109-124. doi:https://doi.org/10.1016/j.esd.2019.02.001

Manandhar, M., Hawkes, S., Buse, K., Nosrati, E., & Magar, V. (2018). Gender, health and the 2030 agenda for sustainable development. Bulletin of the World Health Organization, 96(9), 644-653. doi:10.2471/BLT.18.211607

Martínez-Fernández, J., Banos-González, I., & Esteve-Selma, M. Á. (2021). An integral approach to address socio-ecological systems sustainability and their uncertainties. Science of The Total Environment, 762, 144457. doi:https://doi.org/10.1016/j.scitotenv.2020.144457

Marttunen, M., Lienert, J., & Belton, V. (2017). Structuring problems for Multi-Criteria Decision Analysis in practice: A literature review of method combinations. European Journal of Operational Research, 263(1), 1-17. doi:https://doi.org/10.1016/j.ejor.2017.04.041

Matsumoto, K. i., Hasegawa, T., Morita, K., & Fujimori, S. (2019). Synergy potential between climate change mitigation and forest conservation policies in the Indonesian forest sector: implications for achieving multiple sustainable development objectives. Sustainability Science, 14(6), 1657-1672.

Matthew, O. A., Osabohien, R., Ogunlusi, T. O., & Edafe, O. (2019). Agriculture and social protection for poverty reduction in ECOWAS. Cogent Arts & Humanities, 6(1), 1682107. doi:10.1080/23311983.2019.1682107

May, J. H., Shang, J., Tjader, Y. C., & Vargas, L. G. (2013). A new methodology for sensitivity and stability analysis of analytic network models. European Journal of Operational Research, 224(1), 180-188. doi:https://doi.org/10.1016/j.ejor.2012.07.035

McCollum, D. L., Echeverri, L. G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J., . . . others. (2018). Connecting the sustainable development goals by their energy inter-linkages. Environmental Research Letters, 13(3), 33006-33006.

McGowan, P. J. K., Stewart, G. B., Long, G., & Grainger, M. J. (2019). An imperfect vision of indivisibility in the Sustainable Development Goals. Nature Sustainability, 2(1), 43-45. doi:10.1038/s41893-018-0190-1

Mikhailov, L. (2004). Group prioritization in the AHP by fuzzy preference programming method. Computers & Operations Research, 31(2), 293-301. doi:http://dx.doi.org/10.1016/S0305-0548(03)00012-1

Mikhailov, L. (2004a). A fuzzy approach to deriving priorities from interval pairwise comparison judgements. European Journal of Operational Research, 159(3), 687-704. doi:http://dx.doi.org/10.1016/S0377-2217(03)00432-6

Mikhailov, L. (2004b). Group prioritization in the AHP by fuzzy preference programming method. Computers & Operations Research, 31(2), 293-301. doi:http://dx.doi.org/10.1016/S0305-0548(03)00012-1

Millet, I., & Saaty, T. L. (2000). On the relativity of relative measures – accommodating both rank preservation and rank reversals in the AHP. European Journal of Operational Research, 121(1), 205-212. doi:http://dx.doi.org/10.1016/S0377-2217(99)00040-5

Miola, A., Borchardt, S., Neher, F., & Buscaglia, D. (2019). Interlinkages and policy coherence for the Sustainable Development Goals implementation: An operational method to identify trade-offs and co-benefits in a systemic way. Retrieved from Publications Office of the European Union: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC115163/sdg_interlinkages_jrc115163_final_on_line.pdf

Montibeller, G., & von Winterfeldt, D. (2015). Cognitive and Motivational Biases in Decision and Risk Analysis. Risk Analysis, 35(7), 1230-1251. doi:10.1111/risa.12360

Moreno-Jimenez, J. M., & Vargas, L. G. (1993). A probabilistic study of preference structures in the analytic hierarchy process with interval judgments. Mathematical and Computer Modelling, 17(4–5), 73-81. doi:http://dx.doi.org/10.1016/0895-7177(93)90176-Y

Moreno-Jiménez, J. M., Aguarón, J., & Escobar, M. T. (2008). The Core of Consistency in AHP-Group Decision Making. Group Decision and Negotiation, 17(3), 249-265. doi:10.1007/s10726-007-9072-z

Morton, S., Pencheon, D., & Squires, N. (2017). Sustainable Development Goals (SDGs), and their implementationA national global framework for health, development and equity needs a systems approach at every level. British Medical Bulletin, 124, 81-90.

Motta, R. D. P. S. D. (2019). The sustainable development goals and 1.5°C climate change. World Review of Science, Technology and Sustainable Development, 15(2), 123-144. doi:10.1504/WRSTSD.2019.099375

Mu, E., Cooper, O., & Peasley, M. (2020). Best practices in Analytic Network Process studies. Expert Systems with Applications, 159, 113536. doi:https://doi.org/10.1016/j.eswa.2020.113536

Mustajoki, J., & Marttunen, M. (2017). Comparison of multi-criteria decision analytical software for supporting environmental planning processes. Environmental Modelling & Software, 93, 78-91. doi:https://doi.org/10.1016/j.envsoft.2017.02.026

Nerini, F. F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., . . . others. (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nature Energy, 3(1), 10-15.

Ngarava, S., Zhou, L., Ayuk, J., & Tatsvarei, S. (2019). Achieving food security in a climate change environment: considerations for environmental Kuznets curve use in the South African agricultural sector. Climate, 7(9), 108-108.

Nilsson, M., Griggs, D., Visbeck, M., Skolan för arkitektur och, s., Hållbar utveckling, m. o. t., Kth, & Miljöstrategisk, a. (2016). Map the interactions between Sustainable Development Goals. Nature, 534(7607), 320.

Norton, J. P., Brown, J. D., & Mysiak, J. (2006). To what extent, and how, might uncertainty be defined? Comments engendered by “Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support”: Walker et al., Integrated Assessment 4: 1, 2003. Integrated assessment journal, 6(1), 83-88.

Nugent, R., Bertram, M. Y., Jan, S., Niessen, L. W., Sassi, F., Jamison, D. T., . . . Beaglehole, R. (2018). Investing in non-communicable disease prevention and management to advance the Sustainable Development Goals. The Lancet, 391(10134), 2029-2035.

Obersteiner, M., Walsh, B., Frank, S., Havl\'\ik, P., Cantele, M., Liu, J., . . . others. (2016). Assessing the land resource--food price nexus of the Sustainable Development Goals. Science advances, 2(9), e1501499-e1501499.

Ospina-Forero, L., Castañeda, G., & Guerrero, O. A. (2020). Estimating networks of sustainable development goals. Information & Management, 103342. doi:https://doi.org/10.1016/j.im.2020.103342

Ossadnik, W., Schinke, S., & Kaspar, R. H. (2016). Group Aggregation Techniques for Analytic Hierarchy Process and Analytic Network Process: A Comparative Analysis. Group Decision and Negotiation, 25(2), 421-457. doi:10.1007/s10726-015-9448-4

Ozdemir, M. S., & Saaty, T. L. (2006). The unknown in decision making: What to do about it. European Journal of Operational Research, 174(1), 349-359. doi:http://dx.doi.org/10.1016/j.ejor.2004.12.017

Pandey, U. C., & Kumar, C. (2018). Emerging paradigms of capacity building in the context of climate change. In U. M. Azeiteiro, W. L. Filho, & L. Aires (Eds.), Climate Literacy and

Innovations in Climate Change Education. Distance Learning for Sustainable Development (pp. 193-214): Springer.
Paulson, D., & Zahir, S. (1995). Consequences of uncertainty in the analytic hierarchy process: A simulation approach. European Journal of Operational Research, 87(1), 45-56. doi:http://dx.doi.org/10.1016/0377-2217(94)00044-D
Pedercini, M., Arquitt, S., Collste, D., & Herren, H. (2019). Harvesting synergy from sustainable development goal interactions. Proceedings of the National Academy of Sciences, 116(46), 23021. doi:10.1073/pnas.1817276116
Pedercini, M., Zuellich, G., Dianati, K., & Arquitt, S. (2018). Toward achieving Sustainable Development Goals in Ivory Coast: Simulating pathways to sustainable development. Sustainable Development, 26(6), 588-595. doi:https://doi.org/10.1002/sd.1721
Pöyhönen, M. A., Hämäläinen, R. P., & Salo, A. A. (1997). An Experiment on the Numerical Modelling of Verbal Ratio Statements. Journal of Multi-Criteria Decision Analysis, 6(1), 1-10. doi:10.1002/(SICI)1099-1360(199701)6:1<1::AID-MCDA111>3.0.CO;2-W
Pradhan, P., Costa, L. i., Rybski, D., Lucht, W., & Kropp, J. P. (2017). A systematic study of sustainable development goal (SDG) interactions. Earth's Future, 5(11), 1169-1179.
R Development Core Team. (2014). R: A language and environment for statistical computing and graphics. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.r-project.org/
Ramanathan, R., & Ganesh, L. S. (1994). Group preference aggregation methods employed in AHP: An evaluation and an intrinsic process for deriving members' weightages. European Journal of Operational Research, 79(2), 249-265. doi:http://dx.doi.org/10.1016/0377-2217(94)90356-5
Ramík, J., & Korviny, P. (2010). Inconsistency of pair-wise comparison matrix with fuzzy elements based on geometric mean. Fuzzy Sets and Systems, 161(11), 1604-1613. doi:http://dx.doi.org/10.1016/j.fss.2009.10.011
Ramos, S. B., de Paula Silva, J., Bolela, C. A., & de Andrade, M. (2018). Prediction of Human Development from Environmental Indicators. Social Indicators Research, 138(2), 467-477. doi:10.1007/s11205-017-1693-2
Rao, S., Klimont, Z., Leitao, J., Riahi, K., Van Dingenen, R., Reis, L. A., . . . others. (2016). A multi-model assessment of the co-benefits of climate mitigation for global air quality. Environmental Research Letters, 11(12), 124013-124013.
Recuero Virto, L. (2018). A preliminary assessment of the indicators for Sustainable Development Goal (SDG) 14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development". Marine Policy, 98, 47-57. doi:https://doi.org/10.1016/j.marpol.2018.08.036
Refsgaard, J. C., Van der Sluijs, J. P., Højberg, A. L., & Vanrolleghem, P. (2005). Harmoni-CA Guidance - Uncertainty analysis. Retrieved from http://www.harmoni-ca.info/toolbox/docs/Harmoni-ca_Guidance_1_Uncertainty_Analysis.pdf
Refsgaard, J. C., van der Sluijs, J. P., Højberg, A. L., & Vanrolleghem, P. A. (2007). Uncertainty in the environmental modelling process – A framework and guidance. Environmental Modelling & Software, 22(11), 1543-1556. doi:https://doi.org/10.1016/j.envsoft.2007.02.004
Regan, H. M., Colyvan, M., & Burgman, M. A. (2002). A TAXONOMY AND TREATMENT OF UNCERTAINTY FOR ECOLOGY AND CONSERVATION BIOLOGY. Ecological Applications, 12(2), 618-628.

Reichert, P., Langhans, S. D., Lienert, J., & Schuwirth, N. (2015). The conceptual foundation of environmental decision support. Journal of environmental management, 154, 316-332.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., . . . Foley, J. A. (2009). A safe operating space for humanity. Nature, 461(7263), 472-475.

Rokou, E., Kirytopoulos, K., & Voulgaridou, D. (2012). Analytic Network Process Demystified. Paper presented at the International Federation for Infomation Processing (IFIP) Working Group 8.3: Decision Support Systems, Greece.

Rousseeuw, P., Struyf, A., & Hubert, M. (2014). Cluster Analysis Extended Rousseeuw et al. http://cran.r-project.org/web/packages/available_packages_by_name.html.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15(3), 234-281. doi:http://dx.doi.org/10.1016/0022-2496(77)90033-5

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. European Journal of Operational Research, 48(1), 9-26.

Saaty, T. L. (1995). Decision making for leaders - The Analytic Hierarchy Process for decisions in a complex world (Third edition (extensively revised) ed.): RWS Publications.

Saaty, T. L. (1996). Decision Making with Dependence and Feedback: The Analytic Network Process : the Organization and Prioritization of Complexity: RWS Publications.

Saaty, T. L. (1999a). Basic theory of the analytic hierarchy process: how to make a decision. Revista de la Real Academia de Ciencias Exactas, Físicas y Naturales, 93(4), 395-423.

Saaty, T. L. (1999b). Fundamentals of the Analytic Network Process. Paper presented at the ISAHP 1999, Kobe.

Saaty, T. L. (2007). Time dependent decision-making; dynamic priorities in the AHP/ANP: Generalizing from points to functions and from real to complex variables. Mathematical and Computer Modelling, 46(7–8), 860-891. doi:http://dx.doi.org/10.1016/j.mcm.2007.03.028

Saaty, T. L. (2010). Principia Mathematica Decernendi - Mathematical principles of decision making - Generalization of the Analytic Network Process to neural firing and synthesis. Pittsburg: RWS Publications.

Saaty, T. L., & Begicevic, N. (2010). The scope of human values and human activities in decision making. Appl. Soft Comput., 10(4), 963-974. doi:10.1016/j.asoc.2010.04.002

Saaty, T. L., & Ozdemir, M. S. (2003). Why the magic number seven plus or minus two. Mathematical and Computer Modelling, 38(3), 233-244.

Saaty, T. L., & Peniwati, K. (2013). Group Decision Making: Drawing Out and Reconciling Differences: RWS Publications.

Saaty, T. L., & Tran, L. T. (2007). On the invalidity of fuzzifying numerical judgments in the Analytic Hierarchy Process. Mathematical and Computer Modelling, 46(7–8), 962-975. doi:http://dx.doi.org/10.1016/j.mcm.2007.03.022

Saaty, T. L., & Vargas, L. G. (1984). The legitimacy of rank reversal. Omega, 12(5), 513-516.

Saaty, T. L., & Vargas, L. G. (1993). Experiments on rank preservation and reversal in relative measurement. Mathematical and Computer Modelling, 17(4–5), 13-18. doi:http://dx.doi.org/10.1016/0895-7177(93)90171-T

Saaty, T. L., & Vargas, L. G. (2012). The possibility of group choice: pairwise comparisons and merging functions. Social Choice and Welfare, 38(3), 481-496. doi:10.1007/s00355-011-0541-6

Saaty, T. L., & Vargas, L. G. (2013). Decision Making with the Analytic Network Process: Economic, Political, Social and Technological Applications with Benefits, Opportunities, Costs and Risks: Springer US.

Sachs, J. D., & Sachs, L. E. (2021). Business alignment for the "Decade of Action". Journal of International Business Policy. doi:10.1057/s42214-020-00090-6

Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six Transformations to achieve the Sustainable Development Goals. Nature Sustainability, 2(9), 805-814. doi:10.1038/s41893-019-0352-9

Sadiq, R., & Tesfamariam, S. (2009). Environmental decision-making under uncertainty using intuitionistic fuzzy analytic hierarchy process (IF-AHP). Stochastic Environmental Research and Risk Assessment, 23(1), 75-91. doi:10.1007/s00477-007-0197-z

Salo, A. A., & Hämäläinen, R. P. (1997). On the measurement of preferences in the Analytic Hierarchy Process. Journal of multi-criteria decision analysis, 6, 309-319.

Sava, M. G., Vargas, L. G., May, J. H., & Dolan, J. G. (2020). Multi-dimensional stability analysis for Analytic Network Process models. Annals of Operations Research. doi:10.1007/s10479-020-03553-4

Scherer, L., Behrens, P., de Koning, A., Heijungs, R., Sprecher, B., & Tukker, A. (2018). Trade-offs between social and environmental Sustainable Development Goals. Environmental Science & Policy, 90, 65-72. doi:https://doi.org/10.1016/j.envsci.2018.10.002

Schmoldt, D. L. (2001). The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making: Springer.

Scholz, R. W., & Binder, C. R. (2011). Environmental Literacy in Science and Society: From Knowledge to Decisions: Cambridge University Press.

Schroeder, P., Anggraeni, K., & Weber, U. (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. Journal of Industrial Ecology, 23(1), 77-95. doi:https://doi.org/10.1111/jiec.12732

Schütze, F., Fürst, S., Mielke, J., Steudle, G. A., Wolf, S., & Jaeger, C. C. (2017). The role of sustainable investment in climate policy. Sustainability, 9(12), 2221-2221.

Sebestyén, V., Bulla, M., Rédey, Á., & Abonyi, J. (2019a). Data-driven multilayer complex networks of sustainable development goals. Data in Brief, 25, 104049. doi:https://doi.org/10.1016/j.dib.2019.104049

Sebestyén, V., Bulla, M., Rédey, Á., & Abonyi, J. (2019b). Network model-based analysis of the goals, targets and indicators of sustainable development for strategic environmental assessment. Journal of Environmental Management, 238, 126-135. doi:https://doi.org/10.1016/j.jenvman.2019.02.096

Sediri, S., Trommetter, M., Frascaria-Lacoste, N., & Fernandez-Manjarres, J. (2020). Transformability as a Wicked Problem: A Cautionary Tale? Sustainability, 12(15). doi:10.3390/su12155895

Sen, S. K., & Ongsakul, V. (2018). Clusters of sustainable development goals: A metric for grassroots implementation. Sustainability: The Journal of Record, 11(3), 118-126.

Shahbaz, M., Balsalobre-Lorente, D., & Sinha, A. (2019). Foreign direct Investment–CO2 emissions nexus in Middle East and North African countries: Importance of biomass energy consumption. Journal of Cleaner Production, 217, 603-614. doi:https://doi.org/10.1016/j.jclepro.2019.01.282

Singh, G. G., Cisneros-Montemayor, A. M., Swartz, W., Cheung, W., Guy, J. A., Kenny, T.-A., . . . Ota, Y. (2018). A rapid assessment of co-benefits and trade-offs among Sustainable

Development Goals. Marine Policy, 93, 223-231. doi:https://doi.org/10.1016/j.marpol.2017.05.030

Sinha, A., Sengupta, T., & Alvarado, R. (2020). Interplay between technological innovation and environmental quality: Formulating the SDG policies for next 11 economies. Journal of Cleaner Production, 242, 118549. doi:https://doi.org/10.1016/j.jclepro.2019.118549

Sipahi, S., & Timor, M. (2010). The analytic hierarchy process and the analytic network process: an overview of applications. Management Decisions, 48(5), 775-808.

Skinner, D. J. C., Rocks, S. A., Pollard, S. J. T., & Drew, G. H. (2014). Identifying Uncertainty in Environmental Risk Assessments: The Development of a Novel Typology and Its Implications for Risk Characterization. Human and Ecological Risk Assessment: An International Journal, 20(3), 607-640. doi:10.1080/10807039.2013.779899

Sohl, T.L., Claggett, P.R., 2013. Clarity versus complexity: Land-use modeling as a practical tool for decision-makers. Journal of Environmental Management 129, 235–243.

Spaiser, V., Ranganathan, S., Swain, R. B., & Sumpter, D. J. T. (2017). The sustainable development oxymoron: quantifying and modelling the incompatibility of sustainable development goals. International Journal of Sustainable Development \& World Ecology, 24(6), 457-470.

Srdjevic, B., Srdjevic, Z., & Blagojevic, B. (2014). First-Level Transitivity Rule Method for Filling in Incomplete Pair-Wise Comparison Matrices in the Analytic Hierarchy Process. Appl. Math, 8(2), 459-467.

Stam, A., & Duarte Silva, A. P. (2003). On multiplicative priority rating methods for the AHP. European Journal of Operational Research, 145(1), 92-108. doi:http://dx.doi.org/10.1016/S0377-2217(02)00228-X

Stewart, T., French, S., & Rios, J. (2013). Integrating multicriteria decision analysis and scenario planning-Review and extension. Omega 41(4), 679-688.

Sugihara, K., & Tanaka, H. (2001). Interval Evaluations in the Analytic Hierarchy Process By Possibility Analysis. Computational Intelligence, 17(3), 567-579. doi:10.1111/0824-7935.00163

SuperDecisions. (2019a). SuperDecisions v 3.2.0. https://www.superdecisions.com/downloads/: Creative Decision Foundation.

SuperDecisions. (2019b). Tutorial in complex decision models (ANP). https://www.superdecisions.com/sd_resources/v28_man04.pdf; 03.08.2019.

Swamy, L., Drazen, E., Johnson, W. R., & Bukoski, J. J. (2018). The future of tropical forests under the United Nations Sustainable Development Goals. Journal of Sustainable Forestry, 37(2), 221-256.

Triantaphyllou, E. (2001). Two new cases of rank reversals when the AHP and some of its additive variants are used that do not occur with the multiplicative AHP. Journal of Multi-Criteria Decision Analysis, 10(1), 11-25. doi:10.1002/mcda.284

Triantaphyllou, E., & Sanchez, A. (1997). A Sensitivty Analysis Approach for some deterministic Multi-Criteria Decision-Making methods. Decision Sciences, 28(1), 151-194.

Ulman, S.-R., Isan, V., Mihai, C., & Ifrim, M. (2018). The responsiveness of the rural area to the related-decreasing poverty measures of the sustainable development policy: the case of north-east region of Romania. Transformations in Business & Economics, 17(2B), 780-805.

UN. (1987). Report of the World Commission on Environment and Development: Our Common Future.

UN. (2015). Transforming our world: the 2030 Agenda for Sustainable Development A/RES/70/1. New York: The General Assembly

Uusitalo, L., Lehikoinen, A., Helle, I., & Myrberg, K. (2015). An overview of methods to evaluate uncertainty of deterministic models in decision support. Environmental Modelling & Software, 63, 24-31. doi:https://doi.org/10.1016/j.envsoft.2014.09.017

Vacik, H., & Lexer, M. J. (2001). Application of a spatial decision support system in managing the protection forests of Vienna for sustained yield of water resources. Forest Ecology and Management, 143(1–3), 65-76. doi:http://dx.doi.org/10.1016/S0378-1127(00)00506-5

Vacik, H., Kurttila, M., Hujala, T., Khadka, C., Haara, A., Pykäläinen, J., . . . Tikkanen, J. (2014). Evaluating collaborative planning methods supporting programme-based planning in natural resource management. Journal of Environmental Management, 144, 304-315. doi:http://dx.doi.org/10.1016/j.jenvman.2014.05.029

Vandyck, T., Keramidas, K., Kitous, A., Spadaro, J. V., Van Dingenen, R., Holland, M., & Saveyn, B. (2018). Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. Nature Communications, 9(1), 4939. doi:10.1038/s41467-018-06885-9

Velis, M., Conti, K. I., & Biermann, F. (2017). Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals. Sustainability science, 12(6), 1007-1017.

von Stechow, C., Minx, J. C., Riahi, K., Jewell, J., McCollum, D. L., Callaghan, M. W., . . . Baiocchi, G. (2016). 2° C and SDGs: united they stand, divided they fall? Environmental Research Letters, 11(3), 34022-34022.

Waage, J., Yap, C., Bell, S., Levy, C., Mace, G., Pegram, T., . . . others. (2015). Governing the UN Sustainable Development Goals: interactions, infrastructures, and institutions. The Lancet Global Health, 3(5), e251--e252.

Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M. B. A., Janssen, P., & Krayer von Krauss, M. P. (2003). Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. Integrated Assessment, 4(1), 5-17. doi:10.1076/iaij.4.1.5.16466

Walling, E., & Vaneeckhaute, C. (2020). Developing successful environmental decision support systems: Challenges and best practices. Journal of Environmental Management, 264, 110513. doi:https://doi.org/10.1016/j.jenvman.2020.110513

Walters, L., Balint, P., Stewart, R., & Desai, A. (2011). Wicked Environmental Problems: Managing Uncertainty and Conflict.

Wang, X., van Dam, K. H., Triantafyllidis, C., Koppelaar, R. H. E. M., & Shah, N. (2019). Energy-water nexus design and operation towards the sustainable development goals. Computers & Chemical Engineering, 124, 162-171. doi:https://doi.org/10.1016/j.compchemeng.2019.02.007

Warren, L. (2004). Uncertainties of the Analytic Hierarchy Process. Retrieved from http://www.dsto.defence.gov.au/publications/3476/DSTO-TN-0597.pdf

Warren, L. (2006). Structural uncertainties in numerical induction models. Retrieved from http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA460088

Wątróbski, J., Jankowski, J., Ziemba, P., Karczmarczyk, A., & Zioło, M. (2019). Generalised framework for multi-criteria method selection. Omega, 86, 107-124. doi:https://doi.org/10.1016/j.omega.2018.07.004

Webber, S. A., Apostolou, B., & Hassell, J. M. (1997). The sensitivity of the analytic hierarchy process to alternative scale and cue presentations. European Journal of Operational Research, 96(2), 351-362. doi:http://dx.doi.org/10.1016/S0377-2217(96)00081-1

Wedley, W. C. (1990). Combining qualitative and quantitative factors—an analytic hierarchy approach. Socio-Economic Planning Sciences, 24(1), 57-64. doi:http://dx.doi.org/10.1016/0038-0121(90)90028-6

Wedley, W. C. (1993). Consistency prediction for incomplete AHP matrices. Mathematical and Computer Modelling, 17(4–5), 151-161. doi:http://dx.doi.org/10.1016/0895-7177(93)90183-Y

Weichselgartner, J., & Kasperson, R. (2010). Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. Global Environmental Change, 20(2), 266-277. doi:https://doi.org/10.1016/j.gloenvcha.2009.11.006

Weitz, N., Carlsen, H., Nilsson, M., & Skånberg, K. (2018). Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustainability Science, 13(2), 531-548. doi:10.1007/s11625-017-0470-0

Weitz, N., Persson, Å., Nilsson, M., & Tenggren, S. (2015). Sustainable Development Goals for Sweden: Insights on Setting a National Agenda. SEI Working Paper No. 2015-10. Retrieved from https://www.sei.org/publications/sustainable-development-goals-for-sweden-insights-on-setting-a-national-agenda/

Whitaker, R. (2007a). Criticisms of the Analytic Hierarchy Process: Why they often make no sense. Mathematical and Computer Modelling, 46(7–8), 948-961. doi:http://dx.doi.org/10.1016/j.mcm.2007.03.016

Whitaker, R. (2007b). Validation examples of the Analytic Hierarchy Process and Analytic Network Process. Mathematical and Computer Modelling, 46(7–8), 840-859. doi:http://dx.doi.org/10.1016/j.mcm.2007.03.018

Wieser, A. A., Scherz, M., Maier, S., Passer, A., & Kreiner, H. (2019). Implementation of Sustainable Development Goals in construction industry-a systemic consideration of synergies and trade-offs. Paper presented at the IOP Conf. Series: Earth and Environmental Science.

Wolfslehner, B., Vacik, H., & Lexer, M. J. (2005). Application of the analytic network process in multi-criteria analysis of sustainable forest management. Forest Ecology and Management, 207(1–2), 157-170. doi:http://dx.doi.org/10.1016/j.foreco.2004.10.025

Wydra, K., Jaskolski, M., Wagner, L., & Mohamed, E. S. (2019). Nexus approach to solar technology for energy and water supply for sustainable rural development in Egypt: a review. Journal of Photonics for Energy, 9(4), 43108-43108.

Zaini, S. H. R., & Akhtar, A. (2019). Modelling the sustainable development goals for India - an interpretive structural modelling approach. World Review of Science, Technology and Sustainable Development, 15(1), 46-65. doi:10.1504/WRSTSD.2019.098677

Zelinka, D., & Amadei, B. (2017). A methodology to model the integrated nature of the Sustainable development goals: Importance for engineering education. Paper presented at the ASEE 2017.

Zeshui, X., & Cuiping, W. (1999). A consistency improving method in the analytic hierarchy process. European Journal of Operational Research, 116(2), 443-449. doi:http://dx.doi.org/10.1016/S0377-2217(98)00109-X

Zhang, Q., Liu, S., Wang, T., Dai, X., Baninla, Y., Nakatani, J., & Moriguchi, Y. (2019). Urbanization impacts on greenhouse gas (GHG) emissions of the water infrastructure in China: Trade-offs among sustainable development goals (SDGs). Journal of Cleaner Production, 232, 474-486.

Zhang, Q., Prouty, C., Zimmerman, J. B., & Mihelcic, J. R. (2016). More than target 6.3: a systems approach to rethinking sustainable development goals in a resource-scarce world. Engineering, 2(4), 481-489.

Zhü, K. (2014). Fuzzy analytic hierarchy process: Fallacy of the popular methods. European Journal of Operational Research, 236(1), 209-217. doi:http://dx.doi.org/10.1016/j.ejor.2013.10.034

8 Appendix

8.1 Publication I

Handling a complex agenda: a review and assessment of methods to analyse SDG entity interactions

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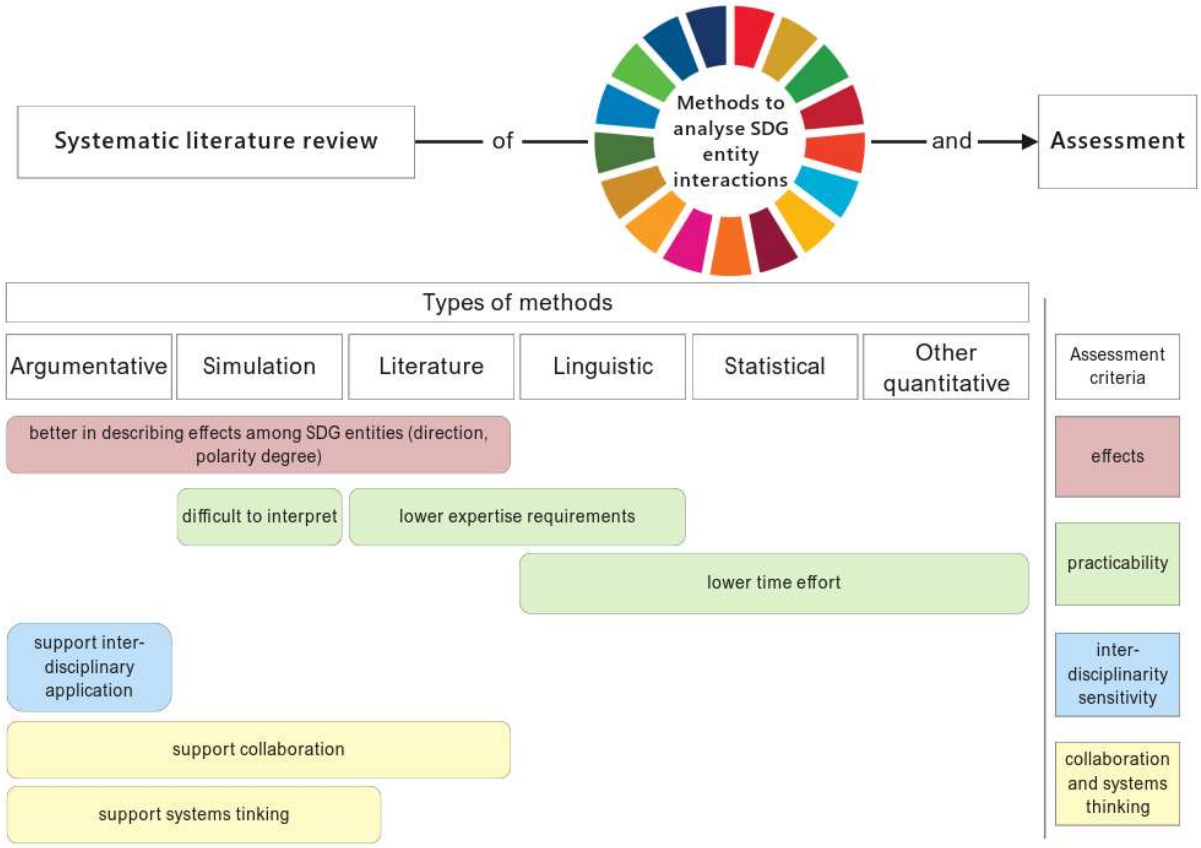
Highlights

- A literature review and assessment was performed to explore SDG entity interactions
- Argumentative, literature and simulation methods are best in analysing interactions
- Statistical methods have lower time requirements
- Argumentative methods encourage interdisciplinarity and collaboration

Graphical abstract



Abstract

The interlinked character of the 2030 Agenda poses both a challenge and an opportunity in terms of coherent policy making. Accordingly, methods in dealing with the interactions between Sustainable Development Goal (SDG) entities (i.e. goals, targets, indicators, policies and external entities) have been the topic of several publications so far.
Here, a review and assessment of methods used for analysing interlinkages between SDG entities is provided. Specifically, we assess the suitability of different methods for addressing policy coherence at different levels and from different perspectives.

Methods used in assessing SDG entity interactions are grouped into argumentative, literature, linguistic, simulation, statistical, and other quantitative methods and are assessed by expert elicitation along a range of criteria according to the following factors: ability to give detailed information about effects between SDG entities, practicability, interdisciplinarity sensitivity, and collaboration and system thinking.

Bearing various advantages and disadvantages, no single method, category or research tradition (i.e. quantitative or qualitative) can be regarded as the inherently most suitable one to analyse SDG entity interactions. Quantitative methods (i.e. statistical, simulation, and other quantitative) are most frequently applied in the scientific context although assessment results suggest that argumentative methods are particularly useful to give information about effects while enabling interdisciplinarity and collaboration. In contrast, literature, linguistic and quantitative methods lack the ability to process different kinds of information and especially statistical and other quantitative methods fail to enhance collaboration and show significant shortcomings in giving detailed information about effects between SDG entities. However, when it comes to the effort required, quantitative methods (except simulation methods) seem to require less resources for application. Although argumentative methods, specifically expert elicitation methods, are evaluated best overall in our assessment, different implementation contexts and importance given to the criteria may justify the application of most other methods as well.

Keywords

SDG entity interactions, interrelations, interlinkages, synergy, trade-off, SDG implementation, policy coherence

1 Introduction

The world is currently confronted with major global challenges: Biodiversity is declining (IPBES, 2019) at extents that gave rise to the notion of a “sixth mass extinction” (Barnosky et al., 2011; Ceballos et al., 2015), and climate is changing at unprecedented rates with the threat of creating a “Hothouse Earth” (Lenton et al., 2019; Steffen et al., 2018). At the same time, social inequalities are rising (Alvaredo et al., 2018). The ongoing COVID-19 crisis exacerbates some of these issues, but also has the potential to open a window of change to overcome some of the challenges (Bacevic, 2020; Hepburn et al., 2020; Klenert et al., 2020; Spash, 2020; Steffen et al., 2020).

In order to tackle the multiple and interlinked problems, the “2030 Agenda for Sustainable Development” (in short: 2030 Agenda), a universal, integrated and indivisible plan containing 17 Sustainable Development Goals (SDGs) and 169 targets, was launched in September 2015 (United Nations, 2015). Connecting the 169 targets both thematically and through several overlaps in their wording (De Paiva Serôa Da Motta, 2019; Le Blanc, 2015; Nugent et al., 2018), the 17 SDGs are cross-linked and form an interwoven network of goals and targets, making for the “integrated” character of the 2030 Agenda. Indivisibility as a principle calls for an integrated implementation of the whole of the 2030 Agenda, thus making it an “Agenda of unprecedented scope and significance” (United Nations, 2015, p. 3).

For the implementation of the SDGs, this integration poses a challenge in terms of policy coherence. However, these interactions are also a chance to identify and make use of synergies and reduce trade-offs between goals and targets. In their report about the world’s progress towards the SDGs the (Independent Group of Scientists appointed by the Secretary-General, 2019, p. xxi) of the United Nations state that the “most efficient – or sometimes the only – way to make progress on a given target is to take advantage of positive synergies with other targets while resolving or ameliorating the negative trade-offs with yet others.”

An important aspect of the integration of the 2030 Agenda lies in relating topics that have been considered and treated as far from each other. Looking at interlinkages can make the entirety of the system visible rather than its parts. Instead of treating policy fields independently with different policies and in different administrative units like ministries, integrated approaches can be designed. For this integration it is important to not consider the SDGs independently, but in relation to others, exhibiting their role in the system. This in turn plays an important role in accomplishing the transformation of the society for a better and just future, as postulated in the 2030 Agenda (United Nations, 2015).

Regarding the 2030 Agenda, there are several entities (SDG entities) that are found to be interlinked. Miola et al. (2019) identify interlinkages between goals, targets, indicators, and what they call “environmental, socio-economic pillars of sustainability” (Miola et al., 2019, p. 9). In addition to goals, targets and indicators, (Bennich et al., 2020) identify SDG policies (i.e. policies to achieve the SDGs) and external entities as potentially interacting entities. External entities are used to analyse interactions in a broader context, e.g. scrutinising the relation between bioeconomy strategies and other SDG entities (Heimann, 2019).

Taking these interlinkages into account, the need for scientific support is often highlighted in order to facilitate the creation of effective and coherent policy strategies. For this reason, but also for reasons of scientific interest in complex systems, the topic attracted strong scientific interest (Allen et al., 2018; Bennich et al., 2020; Breuer et al., 2019; Miola et al., 2019). A variety of methods was developed to systematically identify and assess SDG entity interactions.

Four recent reviews (Allen et al., 2018; Bennich et al., 2020; Breuer et al., 2019; Miola et al., 2019) provide a comprehensive and insightful overview as well as assessments of the SDG literature with varying foci. Allen et al. (2018) focus on the adoption of wide-ranging methods and tools ("evidence- and science-based approaches") in national SDG implementation programs, including but not limited to interactions of SDG entities. They promote system thinking and system analysis approaches but do not provide a systematic comparison or assessment of different methods with respect to SDG entity interactions. Breuer et al. (2019) critically discuss selected methods and issues for analysing SDG entity interactions without providing a systematic and/or exhaustive review. The most comprehensive systematic literature review on SDG entity interactions so far has been published by Miola et al. (2019). They examine and thematically cluster 220 publications, both peer-reviewed and grey literature, related to SDG entity interactions. Their results show SDG coverages, number of trade-offs and synergies identified for the respective publications. Their focus thus lies on a comparison of results from the publications (agreements and disagreements) and their implications for policy making, but not on assessing the methods' ability to elicit SDG entity interactions. Finally, Bennich et al. (2020) propose a "reading guide" for the scientific literature on SDG entity interactions based on a scoping review of 70 peer-reviewed articles. They apply thematic coding to identify major themes in the literature. As Miola et al. (2019), they do not systematically assess the specific properties of different methods in analysing SDG entity interactions, but highlight many important research gaps to improve such an assessment, for example consideration of SDG indicator interactions and truly systemic approaches.

The methods that have been developed so far, span quite a wide range of different approaches with various features. While all methods deal with the interactions of several SDG entities, they differ in the information they can provide about the behaviour and properties of the interactions. They also vary in terms of practicability. Hence, their explanatory power and applicability for SDG implementation differs as well. Moreover, there is a variation in the methods' suitability to promote interdisciplinary approaches or collaboration of experts with the related possible creation of positive side effects like the dissolution of silos and the facilitation of system thinking.

A comprehensive and systematic review and assessment that specifically focuses on these properties according to criteria that are relevant to SDG implementation can provide a basis for selection of a method or a combination of methods to analyse these SDG entity interactions in various contexts. Such a review, however, has not been conducted so far. To address this research gap, our research objectives are thus to (1) conduct a systematic literature review on methods to analyse the following SDG entity interactions: goals, targets, indicators, policies and external entities, (2) identify and categorize the methods applied to analyse such interactions and (3) assess the methods for their suitability to evaluate SDG entity interactions according to various selected criteria. With this review and assessment we aim to answer the following research questions:

- How do methods to analyse SDG entity interactions used in the scientific literature so far differ a) in their ability to give detailed information about effects between SDG entities and b) in their practicability for implementation?
- How do these methods differ in their ability to promote interdisciplinarity and collaboration in order to foster system thinking among the users?

The article is divided into 5 chapters. After the introduction and identification of the research gap (section 1), section 2 presents the methods used to produce the results. These include the systematic literature review (2.1) and the description of the assessment process (2.2). Section 3 highlights the analyses and findings of the study. Finally, in section 4 the discussion and contextualisation of the results in the already existing literature is presented. The article closes with a conclusion and further outlook (section 5).

The research is conducted in the framework of the research project UniNEtZ - Universities and Sustainable Development Goals ("Universitäten und Nachhaltige Entwicklungsziele") (Stötter et al., 2019). In the UniNEtZ-project, the Austrian Federal Ministry of Education, Science and Research has commissioned and funded 17 Austrian universities and research institutions to develop policy options for national SDG implementation. The results from this review helped in designing a process for assessing the interactions between the policy options developed within the UniNEtZ-project and SDG targets, in order to better consider policy coherence (Glatz et al., 2021).

Furthermore, this assessment can support the decision process for one method or a combination of methods to analyse SDG entity interactions in various implementation contexts and thus contributes to furthering evidence-based SDG implementation.

2 Methods

To answer the research questions stated above first a systematic literature review was performed to identify the methods used to analyse SDG entity interactions. These methods were then assessed following defined criteria. The following sections describe the conductance of the literature review and the assessment.

2.1 Systematic literature review

The literature was extracted from the SCOPUS electronic database via the following search string: "Sustainable Development Goals" AND "interlink*" OR "interact*" OR "synerg*" OR "trade-off*" OR "co-benefit*" OR "externalit*". The search was performed on December 16, 2019 and restricted to papers from the establishment of the 2030 Agenda in 2015 onwards. Furthermore, only scientific literature in English was covered. An illustration of the refinement steps is shown in figure 1. The literature search resulted in a collection of 1.744 publications, which were screened for their overall relevance for the review in two steps:

1. Initial screening based on title and abstract
2. Refined screening based on the whole text

The inclusion criteria were as follows:

- The publication assesses interactions between at least two SDG entities, i.e. SDGs, targets, indicators, policies or external entities. SDG policies (i.e. policies designed to act towards achieving an SDG, target or indicator) and external entities are only included in our analysis if they are explicitly assigned to an SDG, target or indicator in the respective publication.
- The analysis of these interactions is methodologically described in the publication.

After this refinement, 93 publications were selected as a final sample for further analysis.

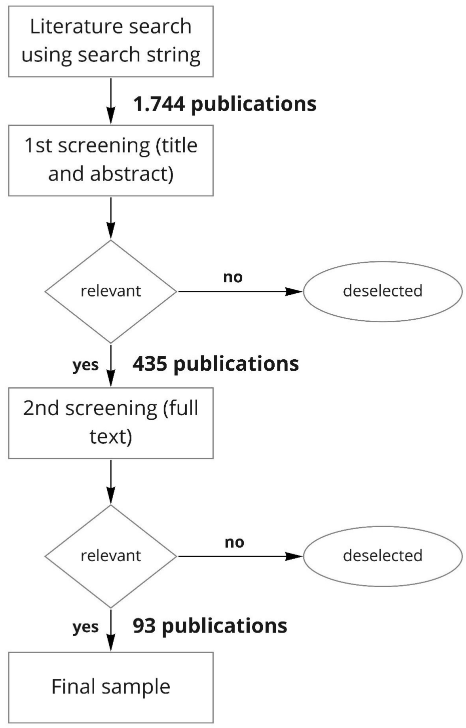


Figure 1: Illustration of the refinement steps and respective retrieved number of publications.

From this set of publications, the methods that were used to analyse SDG entity interactions were retrieved and allocated to six distinct method categories, namely argumentative, literature, linguistic, simulation, statistical, and other quantitative methods. As a basis for the categories already existing classifications from earlier reviews were taken (Bennich et al., 2020; Miola et al., 2019) and adapted to fit the methods that were extracted from the reviewed publications. After discussions among the authors, a consolidated list of methods was compiled (see table 2 for the categories and assigned methods). The methods were briefly described in method fact sheets (see supplementary material), drawing on the publications that they were retrieved from and, in some cases, further literature. The method fact sheets contained a short method description and a summary of the method application in the reviewed publications as well as the scope of application in the SDG context. In combination with discussions these fact sheets were used to gain a common understanding of the methods among the authors to facilitate their assessment.

2.2 Assessment of methods

Based on the method fact sheets and discussions among the authors the methods were assessed using criteria defined by the authors (table 1). The criteria were selected based on Vacik et al. (2014) and adapted to the specific SDG context and our research questions, also taking into account requirements of the UniNEtZ-project as one practical example of the analysis of SDG entity interactions focused on the development of policies for coherent SDG implementation. According to our research questions, the criteria were grouped in effects, practicability, interdisciplinarity sensitivity, and collaboration and system thinking (see table 1 for a deployment of criteria and criterion groups). For the UniNEtZ-project it was particularly crucial to examine the effects criteria (c1-c5), and the interdisciplinarity sensitivity of the methods, i.e. their ability to process different kinds of information (c6-c9), due to the high diversity of disciplinary backgrounds and epistemologies in the project. In particular the effects criteria (c1-c5) and the criterion that tests the ability of a method to enhance system understanding among the users through the process of method application itself (c12) were not used by Vacik et al. (2014) but were developed through discussions among the authors. In order to reflect the variety of disciplines, approaches and epistemologies in UniNEtZ (ranging from arts to technical sciences), the preliminary list of criteria was sent to the coordinators of the SDG groups from the UniNEtZ-project for comments and suggestions for amendments. Comments and suggestions were discussed and a final list of criteria was developed. The assessment criteria are displayed in table 1, for a more detailed description of the criteria, see table A.1.

The assessment process is illustrated in figure 2. Each method was assessed by a group of three experts from the team of authors. First, each person assessed the method independently. Then, the results of the independent assessments were discussed in the assessment group and a consensus assessment for each criterion was agreed upon. There was one assessment group for each method category. In some cases evaluators were members of more than one assessment group, which supported a common understanding of the assessment criteria. For the documentation of the consensus assessment a binary scale (T = true, F = false) was chosen because it supports an easy visualisation of the differences of the various methods. Especially decision makers might find a more detailed classification not practical and useful, as they are primarily interested whether their requirements are met or not. Moreover the binary assessment minimized the time and coordination effort for the experts in the assessment group, as consensus was achieved more easily. Only the time effort (c19) was assessed on a scale from 1 (low time effort) to 4 (high time effort). Additionally, the context dependency of the rating for each criterion was assessed on a scale from 1 (very low context dependency) to 4 (very high context dependency). A high context dependency indicates that the method can be applied in multiple ways and different specific application contexts that make a definite evaluation (true or false) of the criterion difficult.
It is important to note that the assessment was performed at the level of methods, not at the level of publications, considering that one publication can use a combination of more than one method.

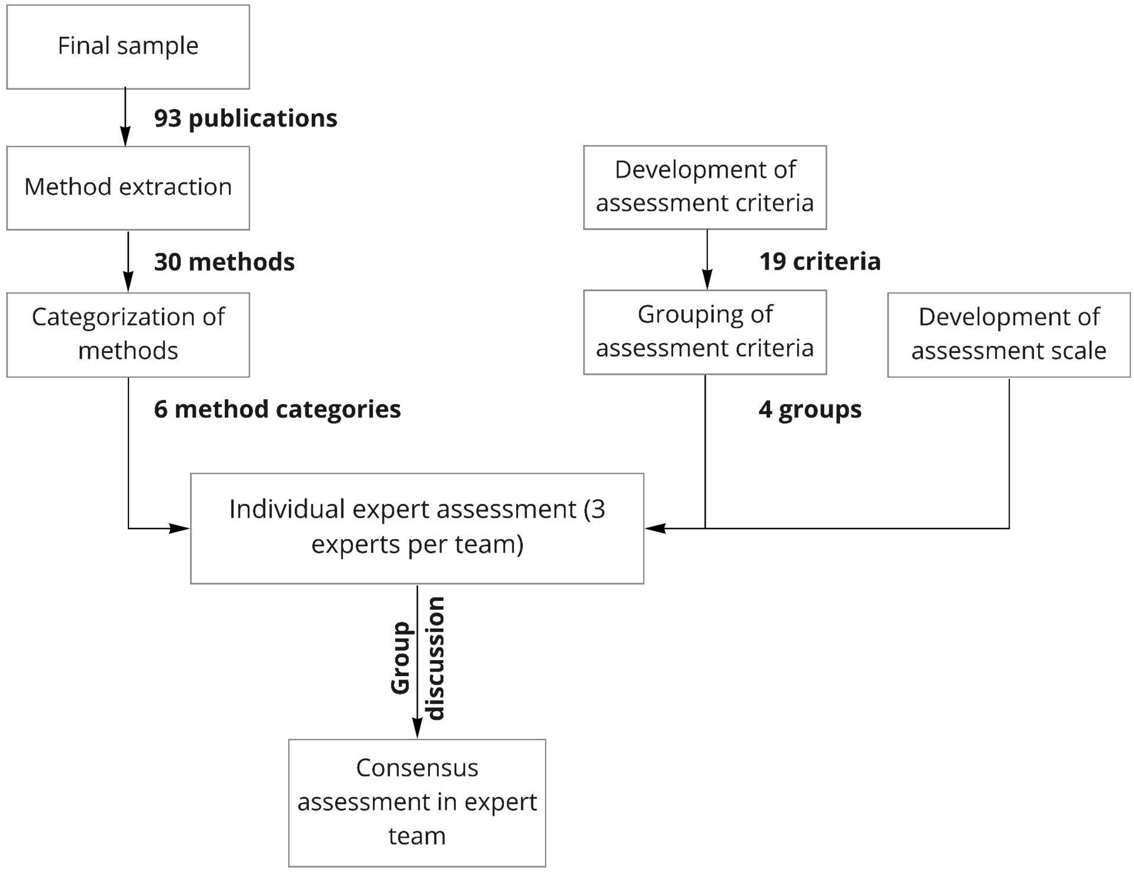


Figure 2: Stepwise illustration of the assessment process for each method. For each method category there was one assessment group.

In addition to the assessment of methods along the criteria (table 1) the fulfilment rates were calculated for the specific criterion groups (i.e. effects, interdisciplinarity sensitivity, practicability, and collaboration and system thinking). To do this, “true” and “false” were equalled with a value of 1 and 0, respectively. Values were aggregated in each criterion group for each method and normalised. In one comprehensive formula, for each criterion group *cg*, the rating *R* corresponding to method *m* is thus given by

Eq. 1:

$$R_{cg,m} = \frac{\sum_{i}^{N_{cg}} s_{cg,i,m} - \min_{m}\left(\sum_{i}^{N_{cg}} s_{cg,i,m}\right)}{\max_{m}\left(\sum_{i}^{N_{cg}} s_{cg,i,m}\right) - \min_{m}\left(\sum_{i}^{N_{cg}} s_{cg,i,m}\right)}$$

where *i* enumerates the sub-criteria within each criterion group, N_{cg} is the number of sub-criteria within the criterion group, *cg* is the binary rating of the *i*th sub-criterion within criterion group *cg* for method *m*, and *min* and *max* are minimum and maximum ratings, respectively, taken over all methods *m*, of the summed binary ratings. A value of 1 means that the respective method fulfilled the most criteria of a criterion group compared to the other methods and 0 means that the method fulfilled the least criteria.

3 Results

3.1 Systematic review of methods used to analyse SDG entity interactions

From the 93 selected publications, 30 methods were extracted and assigned to 6 categories, i.e. argumentative, literature, linguistic, simulation, statistical, and other quantitative methods. The categories and assigned methods are displayed in table 2. The categories including the most methods were statistical, simulation, and argumentative methods. Statistical and simulation methods together accounted for 57% of the methods used for the analysis of SDG entity interactions. These were also the approaches that were most frequently used together with literature methods (22% of the publications in the statistical, 21% publications in the literature and 20% in the simulation category). The portion of publications per method category are displayed in the pie chart in figure 3. “Other quantitative methods” were used by 17% of the publications, although this group only consisted of three methods among which network analysis was used most frequently out of all methods (in 16 publications). The number of publications per method is shown in the bar chart in figure 3. Apart from Network analysis (NWA), Integrated assessment models (IAM), Non-systematic literature reviews (Non-syst), and scoring techniques using the Nilsson scale were the most frequently used methods in the reviewed publications.

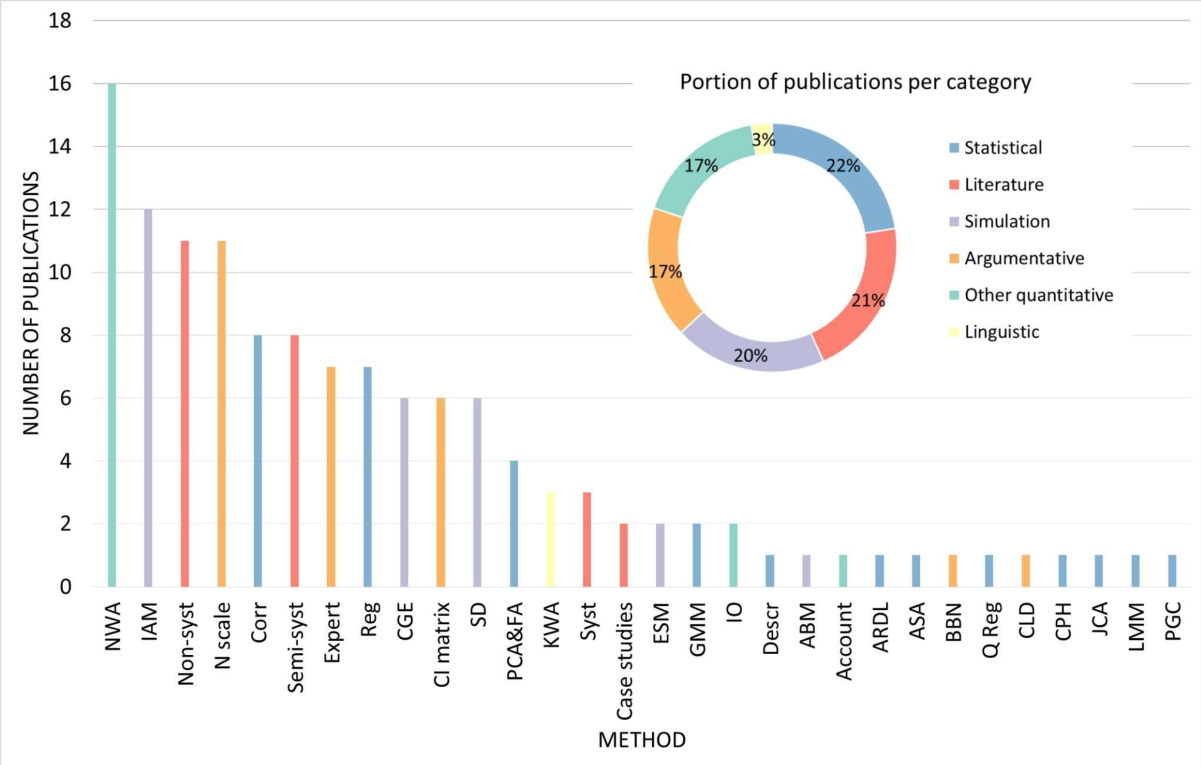


Figure 3: Number of publications per method. The bar chart shows the number of publications that applied a certain method. The pie-chart shows the portion of publications as a percentage of all the reviewed publications that used a method assigned to a certain method category. (ABM = Agent based modelling, Account = Accounting framework, ARDL = Autoregressive distributive lag bounds test, ASA = Advanced sustainability analysis, BNN = Bayesian belief network, Case studies = Review of case studies, CGE = Computable general equilibrium models, CI matrix = Cross-impact matrix, CLD = Causal loop diagram, Corr = Correlation analysis, CPH = Cox proportional hazards models, Descr = Descriptive statistics, ESM = Energy system models, Expert = Structured elicitation of expert information, GMM = Generalized method of moments, IAM = Integrated assessment models, IO = Environmentally-extended multi-regional input-output models, JCA = Joint correspondence analysis, KWA = Keyword analysis, LMM = Linear mixed effect models, N scale = Nilsson scale, Non-syst = Non-systematic literature review, NWA = Network analysis, PCA&FA = Principal component analysis and Factor analysis, PGC = Pairwise granger causality test, Q Reg = Quantile regression, bootstrapped, Reg = Regression analysis, SD = System dynamics modelling, Semi-syst = Semi-systematic literature review, Syst = Systematic literature review)

Statistical methods were the category with the greatest number of methods, 40% of all methods belonged to this category. However, in comparison with other categories, these methods were more similar to each other in their characteristics, as shown in the assessment below.

28% of the reviewed publications reported a multi-method approach indicating the application of more than one method. 18% of the publications used two methods, 9% three methods and 1% applied 4 methods. A closer look at the multi-method approaches showed that specific bundles of methods were used combined and reported in different publications. Evidently, the bundle of methods embracing a scoring with the Nilsson scale with the subsequent application of a CI-matrix and a network analysis as well as the combined application of structured elicitation of expert information and scoring with the Nilsson scale were reported three times which is the most often of all method bundles. However, these bundles overlapped and were reported in publications applying three or four methods.

3.2 Assessment of methods to analyse SDG entity interactions

The results of the assessment process are displayed in the matrix shown in figure 4. “True” ratings are depicted in orange and “false” ratings in violet. A more detailed description of the results for each method category is provided in Appendix C.

While quantitative methods (i.e. statistical, simulation, and other quantitative methods) formed a rather uniform group in terms of their assessment, argumentative methods and document based methods (i.e. literature and linguistic methods) gave a much more mixed picture. In general, however, they fulfilled more criteria, except for the linguistic method Keyword analysis (KWA). Particularly, argumentative methods had a particularly high fulfilment rate in comparison with other method categories. Though, when it comes to context dependency, they mostly had higher ratings than other groups. Low context dependencies were especially shown for statistical and other quantitative methods, and also the simulation methods were, with the exception of some criteria and single methods, quite little dependent on the context. One reason for this might be that the quantitative methods in general were defined more strictly, as e.g. statistical methods represented statistical calculation procedures. In contrast, argumentative and literature methods, due to their high variety in application cases, were often pooled into bigger groups. Moreover, the literature methods were, at times, not very well described in the reviewed publications, which was especially the case for non-systematic and semi-systematic literature reviews. Some of the methods can also be used as a form of representation (e.g. Network analysis), which depends on the way the method is used. For our assessment only forms of method application where new information is created were considered.

Figure 5 shows the normalised ratings for the criterion groups. For a depiction of the aggregated ratings across criterion groups see figure B.3 in Appendix B. Argumentative methods performed best when considering all criteria in total. They had particularly high ratings in the effects and the collaboration and system thinking groups. Literature and simulation methods had high ratings in the effects group and ranked middle in collaboration and system thinking. Both showed a rather low fulfilment of interdisciplinarity sensitivity. Practicability was higher for literature methods compared to simulation methods. For the linguistic method practicability was the only criterion group where it ranked high. Statistical and other quantitative methods had a rather low fulfilment of criteria compared to the other groups. Especially statistical methods ranked particularly low in interdisciplinarity sensitivity and collaboration and system thinking. However, their practicability was mid-table.

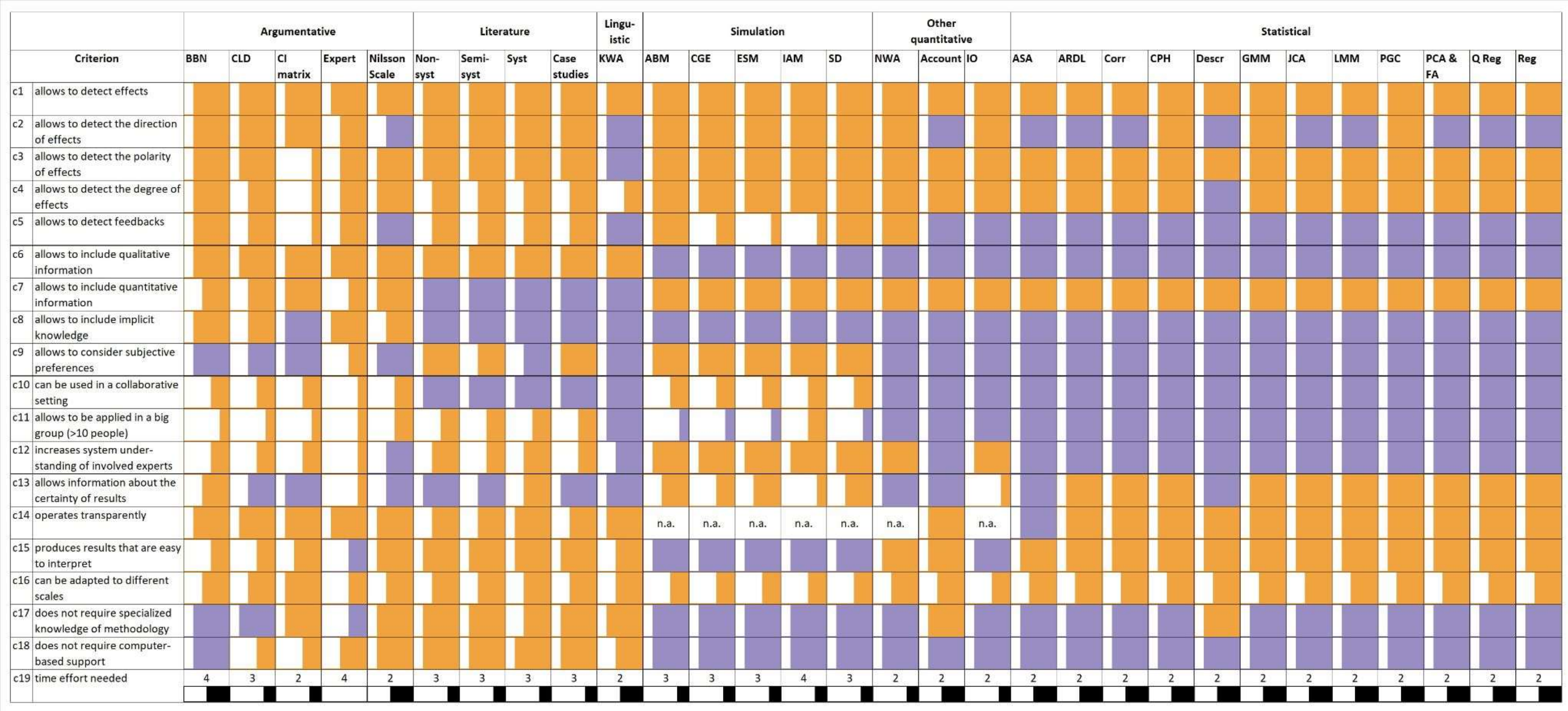


Figure 4: Assessments of methods regarding the predefined criteria including context dependency of assessments. "True" ratings are depicted in orange and "false" ratings in violet. The white bars indicate the degree of context dependency that was assessed using a scale from 1 to 4 (1 = very low, 2 = relatively low, 3 = relatively high, 4 = very high context dependency). The longer the white bar, the higher the context dependency of the rating was assessed. The white bar on black background depicts the context dependency of the ratings for c19 (time effort needed). Time effort was assessed using a scale from 1 to 4 (1 = very low, 2 = relatively low, 3 = relatively high, 4 = very high time effort).

Criterion group	Argumentative: Bayesian belief network	Argumentative: Causal loop diagram	Argumentative: Cross-impact matrix	Argumentative: Structured elicitation of expert information	Argumentative: Nilsson scale	Literature: Literature review - overview	Literature: Narrative literature review	Literature: Systematic literature review	Literature: Review of case studies	Lingu-istic: Keyword analysis
Effects	1	1	1	1	0,3333	1	1	1	1	0
Interdisciplinarity sensitivity	0,6667	0,6667	0,3333	1	0,6667	0,3333	0,3333	0	0,3333	0
Collaboration and systems thinking	1	1	1	1	0,6667	0,6667	0,6667	0,6667	0,6667	0
Practicability	0,4706	0,5294	0,8235	0,4706	0,8235	0,7647	0,7647	1	0,7647	0,8235
Sum ∑	**2,6667**	**2,6667**	**2,3333**	**3**	**1,6667**	**2**	**2**	**1,6667**	**2**	**0**

Criterion group	Simulation: Agent based modelling	Simulation: Computable general equilibrium models	Simulation: Energy system models	Simulation: Integrated assessment models	Simulation: System dynamics modelling	Other quantitative: Network analysis	Other quantitative: Accounting framework	Other quantitative: Environmentally-extended multi-regional input-output models
Effects	1	1	1	1	1	1	0,3333	0,6667
Interdisciplinarity sensitivity	0,3333	0,3333	0,3333	0,3333	0,3333	0	0	0
Collaboration and systems thinking	0,6667	0,6667	0,6667	1	0,6667	0,3333	0	0,3333
Practicability	0,0588	0,0588	0,0588	0	0,0588	0,1176	0,5882	0,1176
Sum ∑	**2**	**2**	**2**	**2,3333**	**2**	**1,3333**	**0,3333**	**1**

Criterion group	Statistical: Advanced sustainability analysis	Statistical: ARDL bounds test	Statistical: Correlation analysis	Statistical: Cox proportional hazards models	Statistical: Descriptive statistics	Statistical: Generalized method of moments	Statistical: Joint correspondence analysis	Statistical: Linear mixed effect model	Statistical: Pairwise granger causality test	Statistical: Principle component analysis / Factor analysis	Statistical: Quantile regression, bootstrapped	Statistical: Regression analysis
Effects	0,3333	0,3333	0,3333	0,6667	0	0,6667	0,3333	0,3333	0,6667	0,3333	0,3333	0,3333
Interdisciplinarity sensitivity	0	0	0	0	0	0	0	0	0	0	0	0
Collaboration and systems thinking	0	0	0	0	0	0	0	0	0	0	0	0
Practicability	0,1176	0,5882	0,5882	0,5882	0,5882	0,5882	0,5882	0,5882	0,5882	0,5882	0,5882	0,5882
Sum ∑	**0,3333**	**0,3333**	**0,3333**	**0,6667**	**0**	**0,6667**	**0,3333**	**0,3333**	**0,6667**	**0,3333**	**0,3333**	**0,3333**

Figure 5: Normalised ratings for the specific criterion groups for each method. "True" ratings were equalled with a value of 1 and "false" ratings were equalled with 0. Then the ratings were aggregated among criterion groups and normalised. 1 = highest fulfilment of criteria in the respective criterion group by the respective method compared to other methods; 0 = lowest fulfilment of criteria in the respective criterion group by the respective method compared to other methods. Different colour shades indicate the degree of fulfilment of criterion groups (blue) or all criteria (red), respectively, of a certain method. Darker shades indicate a higher fulfilment.

3.2.1 The methods‘ practicability and ability to give detailed information about effects between SDG entities

The effects criteria (c1-c5) showed a rather high fulfilment for most of the categories, especially for argumentative, literature and simulation methods. However, there were significant differences. Statistical methods were mostly not able to detect the direction of effects (c2) and feedback loops (c5). Only Cox proportional hazards models (CPH), Generalized method of moments (GMM), and Pairwise granger causality test (PGC) fulfilled c2. From the remaining methods only the Nilsson scale (argumentative methods), KWA (linguistic methods), and Accounting framework (other quantitative methods) lack these properties (c2 and c5). The linguistic method KWA additionally is the only method that is not able to give information about the polarity of effects (c3), i.e. whether the relation between SDG entities is enhancing or counteracting.

Regarding practicability for implementation (practicability criteria, c13-c19), statistical and other quantitative methods exhibit some advantages, as transparency (c14), scalability (c16), the inclusion of certainty measures (c13) and the ease of interpretation (c15) was given for most or all methods. Moreover, those were the categories where time effort (c19) was estimated the lowest. Other categories displayed a considerably higher time effort but were mostly estimated to be easier in application, as computer support (c18) and specialized knowledge (c17) is not needed that often. One exception is the simulation category, which combines a high time effort (c19) with the need for specialized knowledge (c17) and computer-based support (c18). Furthermore, results obtained through these methods are often difficult to interpret (c15). This makes them rank last in terms of practicability, whereas argumentative and literature methods as well as the linguistic method KWA performed quite well regarding the practicability criteria. They operate transparently (c14), are scalable (c16), and most of them are easy to interpret (c15). Time effort (c19), however, is still quite high and the possibility to include certainty measures is mostly lacking (c13).

3.2.2 The methods’ ability to support interdisciplinarity and collaboration

In terms of interdisciplinarity sensitivity (c6-c9), argumentative methods performed best in our assessment. They are able to include the biggest range of different kinds of information, as compared to other categories. On the contrary, all the other categories could either only incorporate quantitative or qualitative data into their assessment.

Moreover, argumentative methods are able to support collaboration among experts by enabling its use in big groups (c11) and collaborative settings (c10). This, and their sensitivity to interdisciplinarity can in turn contribute to their ability to increase system understanding among the users through the process of method application itself apart from the results that the method provides (c12). For these collaboration and system thinking criteria (c10-c12) argumentative methods also showed the highest fulfilment among method categories. Statistical, other quantitative methods and KWA mostly did not meet the criteria, most simulation methods are not applicable in big groups (c11) although they are mostly used in collaborative settings (c10). The literature methods, by contrast, do not encourage their use in collaborative settings. Some collaboration, however, might be possible if more people are involved and discussions take place. But this is not necessarily part of the methods.

4 Discussion

The following section provides a discussion of our assessment results along the research questions including further literature. Although the team working on the systematic literature review and the description and assessment of the methods was considerably large (15 people) and covered various disciplines, in some parts of the assessment expertise was limited concerning certain methods. The method fact sheets (see supplementary material), that were designed to describe the methods and serve as a basis for our assessment, were based on the reviewed publications and some further literature. They do not, and also don't mean to, give a comprehensive scientific treatise of the method. An additional limitation of our research stems from the decision to evaluate the methods using a binary scale. The choice for a more nuanced scale would allow to generate a more detailed picture of the methods properties. However, the binary scale was chosen because it is the best compromise to detect basic differences of the methods and to be simply and fast-forward applied by the author team.

4.1 The methods' practicability and ability to give detailed information about effects between SDG entities

While all methods reviewed in this publication deal with the interaction of SDG entities and therefore seek to provide information about the effects that these entities have on each other, they differ in their ability to examine these effects in more detail. All the methods give information about the effects in some way, like the presence of effects (c1) and their polarity (c3). However, in detecting the direction of effects (c2) and feedback loops (c5), lots of methods were rather limited, which is also pointed out by other reviews (Breuer et al., 2019; Ospina-Forero et al., 2020).Those criteria were mostly fulfilled by argumentative, literature and simulation methods. However, argumentative methods might be more prone to bias and limited in transparency due to their reliance on expert judgement (Breu et al., 2021; Ospina-Forero et al., 2020).

For the practicability criteria (c13-c19), scalability (c16), i.e the ability to adjust the method to various temporal and spatial levels, was given for all methods in our assessment. Ospina-Forero et al. (2020) have contradicting outcomes in this regard, where they find problems for all the methods they reviewed. But they focus more on the probable circumstances and presumed practical problems of applicability (e.g. availability of data and experts in a country) than on the possibilities of the method itself.

Statistical, other quantitative methods, and the linguistic method KWA are faster in application (c19) but, together with simulation methods, require more specialization and computer support (c17, c18). While simulation methods additionally require a high amount of time (c19), argumentative and literature methods do so too, but most of them are easier in application (c17, c18). Simulation methods therefore are the most resource-intensive group (in terms of time, facilities and expertise required), which is also supported by Allen et al. (2021).

Allen et al. (2021), performed an analysis of Voluntary National Reports regarding the methods that were consulted in the reports. According to them, quantitative methods, like statistical methods or dynamic modelling methods (i.e. simulation), are used much less frequently for national implementation of the SDGs than qualitative methods, like conceptual frameworks or mappings (Allen et al., 2021). However, the scientific literature provides a considerably more extensive body of quantitative methods. This discrepancy might derive from the higher demand of resources needed for implementation (c17-c19) and especially their higher amount of complexity (i.e. expertise needed - c17, results that are more difficult to interpret - c15). Considering this, qualitative approaches might be more attractive to decision makers and therefore have a greater impact on national implementation.

We limited our selection of publications for the review on scientific literature in English. This means that grey literature, like national reports, were not included. Those could have brought more insight into which methods were used to consider policy coherence in national implementation strategies. Our focus on English literature further ruled out publications that were more directed towards a local or regional level.

The degree of detail of the information given by the method might be a crucial prerequisite to apply science-based approaches for SDG implementation. While the vast majority of studies test the interactions between SDGs, targets or indicators, only few use their methods to illuminate interlinkages of policies or measures to achieve the SDGs with other SDG entities (Collste et al., 2017; Howden-Chapman et al., 2020; Pedercini et al., 2019, 2018). This, however, could be essential to gain knowledge about the actual effects such policies/measures have, including their interaction with the SDGs. Not all of the methods reviewed and assessed in this publication are suitable to analyse these interactions and those methods that can analyse interactions between policies and other SDG entities have certain advantages and disadvantages in doing so. They deliver more specific information for policy making but often require more time and expertise. Statistical methods are limited because usually indicator data is used to calculate statistical relations between SDGs or targets. Methods would need to anticipate the effect of SDG policies on the indicators which is difficult using only statistical methods. This limitation is also reflected in the inability of most statistical methods to identify the direction of effects (c2).

Also the linguistic method KWA is not very suitable to estimate the interactions of SDG policies, because it fails to detect the direction (c2) and polarity (c3) of effects. Instead, argumentative, literature and simulation methods are better suited for this endeavour, when accepting their disadvantages, such as a considerably higher time effort (c19).

4.2 The methods' ability to support interdisciplinarity and collaboration

While detailed information is important for the development and implementation of policies to achieve the SDGs, the promotion of a more holistic interdisciplinary approach supporting horizontal integration across institutions and ministries is also required in order to undertake the necessary transformation.

The ability of a method to include different kinds of information (c6-c9) and hence, to be applicable to scientists from various disciplines plays a crucial role in supporting interdisciplinary work. A requirement for interdisciplinarity is the abundance of disciplinary knowledge (Posch et al., 2006). This knowledge is created and used by scientists having different approaches to theories and using different kinds of methods (Brown et al., 2015). To work together, a common ground needs to be built. Methods that have the ability to include quantitative as well as qualitative information can therefore support the integration of several approaches and disciplines. This in turn can facilitate and in some cases be a prerequisite for widespread collaboration among experts. In our assessment only argumentative methods were suitable for integrating various kinds of data and thus support an interdisciplinary application (c7-c9). Together with simulation methods, they were also much more qualified to enhance collaboration among experts (c10), to be applied in big groups (c11), and to increase system understanding among users through the process of method application (c12). The latter two also held true for literature methods.

Sustainability problems are complex, dynamic, non-linear and ill-defined, also referred to as "wicked" (based on Rittel and Weber, 1973). Therefore, it is difficult, if not impossible, for one discipline alone to solve these issues. Hence, interdisciplinary collaboration is needed incorporating a variety of competences (Annan-Diab and Molinari, 2017; Brown et al., 2015; Posch et al., 2006). This collaboration can enhance the societal impact of research outcomes (Brown et al., 2015) and also broaden the experts' approach towards the topic, enhancing their systems thinking ability and giving them a more holistic view on the 2030 Agenda in general. As systems thinking is regarded as one of the key competences for sustainability (Brundiers et al., 2021; Wiek et al., 2011), interdisciplinary research is expected to produce better, more effective solutions. Moreover, broadening the researchers' perspectives can contribute to dissolving disciplinary silos and lead to more systemic research and consequently more systemic policy advice. Systemic research and policy advice is what is needed, especially when it comes to the development of policies and measures to achieve the SDGs. It can promote the essential horizontal policy integration, i.e. linking themes and sectors, institutions and ministries, and give an inspiration for designing governance systems for SDG implementation that make use of synergies and minimize trade-offs.

The variety of methods already used to analyse SDG entity interactions bear diverse strengths and weaknesses as explained above and described in more detail in Appendix C. Multi-method-approaches, already applied by 28% of the reviewed publications (such as by Hazarika and Jandl, 2019; Lusseau and Mancini, 2019; Weitz et al., 2018) have the possibility to make use of the advantages of more than one method while compensating for its disadvantages (Von Wehrden et al., 2017). Former considerations about the integration of quantitative and qualitative research methods provide information on how to combine methods, e.g. to validate results, examine issues from different perspectives to gain broader and deeper information, or to re-examine assumptions preceding the analysis (Kelle and Erzberger, 1999). For this integration, openness and exchange between scientific communities is key (Kelle and Erzberger, 1999; Mahoney and Goertz, 2006). Interdisciplinarity can contribute to this exchange.

4.3 Relation to the UniNEtZ-project

Our work in the UniNEtZ-project served as an impetus for this review and assessment of methods to identify SDG entity interactions and therefore also had great impact on the aims of our research, our approach towards the topic and the results we gained. One of the central aims of the project was to develop policy options for national implementation of the SDGs in Austria. In order to provide comprehensive advice for a coherent policy strategy, information about the effects and interactions of the developed policies was required. To be able to make an informed decision about which method to use to analyse these interactions, the present review and assessment was initiated (Glatz et al., 2021). The requirements of the UniNEtZ-project, inspired our analysis in various ways. First of all, our research questions reflect the overall aim of the project to create policy advice. Hence, detailed information on effects and the practicability for implementation constituted central aspects of our analysis. Moreover, the interdisciplinarity of the UniNEtZ-project, and consequently our research team, increased our consciousness for the importance of interdisciplinarity and collaboration to support transformative research and policy making and thus found entrance in our research questions and criteria. For the assessment of policy options regarding their effects on SDG targets in UniNEtZ, finally a combination of argumentative methods was chosen. One reason for this decision was the applicability of argumentative methods for a multitude of disciplines, being able to incorporate several kinds of data (c6-c9). But also the ability to give detailed information about effects (in particular c1-c4) and the easiness of interpretation of results (c12) played a central role in the selection.

5 Conclusions

A variety of methods exist in the scientific literature to analyse SDG entity interactions. The majority of which are quantitative methods with statistical methods constituting the biggest group. Bearing various advantages and disadvantages, no single method, category or research tradition (i.e. quantitative or qualitative) can be regarded as the inherently most suitable one to analyse SDG entity interactions. Rather, it depends on the context of the analysis: which entities are to be analysed, time scales and spatial scales, resources, and requirements for interdisciplinarity. Several methods can contribute to SDG implementation and the transformation of society in different ways with different foci. Some methods, like simulation, literature and argumentative methods, have the ability to give more detailed information on SDG policy interactions and thus support policy creation and adoption, whereas most statistical methods and the linguistic method are considerably limited in this regard. Apart from the ability to give detailed information, for SDG implementation practicability also plays an important role. Hereof, qualitative methods like argumentative, literature and linguistic methods show considerable benefits due to their lower complexity compared to statistical, simulation and other quantitative methods. However, the methods belonging to the statistical and other quantitative methods have the simple benefit of being less time and resource intensive. Some methods, like many of those belonging to the category of argumentative methods, can support interdisciplinarity and collaboration. This has the possibility to promote more systemic thinking among scientists, lead to a dissolution of silos, enhance the conduction of systemic research and policy advice by researchers and consequently result in more comprehensive policy making. Quite often, a combination of methods from different categories or even research traditions can be useful to get the best information about existing SDG entity interactions. This can be supported by interdisciplinary approaches.

Our research adds to making existing methods to analyse SDG entity interactions more usable for decision makers in practice by shedding light to their strengths and weaknesses concerning their practicability as well as their ability to give concrete and valuable information for policy development. At the same time the assessment gives information about the methods' capacity to facilitate holistic approaches in order to accomplish transformative change.

Acknowledgements

We would like to thank Marianne Penker, Carmen Séra and Anna-Katharina Brenner for their helpful comments during the preparation of the article.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Allen, C., Metternicht, G., Wiedmann, T., 2021. Priorities for science to support national implementation of the sustainable development goals: A review of progress and gaps. Sustainable Development.

Allen, C., Metternicht, G., Wiedmann, T., 2018. Initial progress in implementing the Sustainable Development Goals (SDGs): a review of evidence from countries. Sustainability Science 13, 1453–1467.

Alvaredo, F., Chancel, L., Piketty, T., Saez, E., Zucman, G., 2018. The Elephant Curve of Global Inequality and Growth. AEA Papers and Proceedings 108, 103–108. https://doi.org/10.1257/pandp.20181073

Annan-Diab, F., Molinari, C., 2017. Interdisciplinarity: Practical approach to advancing education for sustainability and for the Sustainable Development Goals. The International Journal of Management Education 15, 73–83.

Bacevic, J., 2020. Unthinking knowledge production: from post-Covid to post-carbon futures. Globalizations 1–13. https://doi.org/10.1080/14747731.2020.1807855

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B., Ferrer, E.A., 2011. Has the Earth's sixth mass extinction already arrived? Nature 471, 51–57. https://doi.org/10.1038/nature09678

Bennich, T., Weitz, N., Carlsen, H., 2020. Deciphering the scientific literature on SDG interactions: A review and reading guide. Science of the Total Environment 138405.

Breu, T., Bergöö, M., Ebneter, L., Pham-Truffert, M., Bieri, S., Messerli, P., Ott, C., Bader, C., 2021. Where to begin? Defining national strategies for implementing the 2030 Agenda: the case of Switzerland. Sustainability science 16, 183–201.

Breuer, A., Janetschek, H., Malerba, D., 2019. Translating Sustainable Development Goal (SDG) Interdependencies into Policy Advice. Sustainability 11, 2092. https://doi.org/10.3390/su11072092

Brown, R.R., Deletic, A., Wong, T.H., 2015. Interdisciplinarity: How to catalyse collaboration. Nature News 525, 315.

Brundiers, K., Barth, M., Cebrián, G., Cohen, M., Diaz, L., Doucette-Remington, S., Dripps, W., Habron, G., Harré, N., Jarchow, M., others, 2021. Key competencies in sustainability in higher education—toward an agreed-upon reference framework. Sustainability Science 16, 13–29.

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M., 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. Sci. Adv. 1, e1400253. https://doi.org/10.1126/sciadv.1400253

Collste, D., Pedercini, M., Cornell, S.E., 2017. Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. Sustainability science 12, 921–931.

De Paiva Serôa Da Motta, R., 2019. The sustainable development goals and 1.5° C climate change. World Review of Science, Technology and Sustainable Development 15, 123–144.

Engström, R.E., Howells, M., Destouni, G., 2018. Water impacts and water-climate goal conflicts of local energy choices--notes from a Swedish perspective. Proceedings of the International Association of Hydrological Sciences 376, 25–33.

Gabbert, S., Van Ittersum, M., Kroeze, C., Stalpers, S., Ewert, F., Olsson, J.A., 2010. Uncertainty analysis in integrated assessment: the users' perspective. Regional Environmental Change 10, 131–143.

Glatz, I., Allerberger, F., Fehr, F., Gratzer, G., Horvath, S.-M., Keller, L., Kreiner, H., Kromp-Kolb, H., Lang, R., Liedauer, S., others, 2021. Den 17 Nachhaltigen Entwicklungszielen den Weg bereiten: UniNEtZ: der Weg von der Theorie in die Praxis. GAIA-Ecological Perspectives for Science and Society 30, 54–56.

Hazarika, R., Jandl, R., 2019. The Nexus between the Austrian Forestry Sector and the Sustainable Development Goals: A Review of the Interlinkages. Forests 10. https://doi.org/10.3390/f10030205

Heimann, T., 2019. Bioeconomy and SDGs: Does the Bioeconomy Support the Achievement of the SDGs? Earth's Future 7, 43–57. https://doi.org/10.1029/2018EF001014

Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., Zenghelis, D., 2020. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? Oxford Review of Economic Policy 36, S359–S381. https://doi.org/10.1093/oxrep/graa015

Howden-Chapman, P., Keall, M., Whitwell, K., Chapman, R., 2020. Evaluating natural experiments to measure the co-benefits of urban policy interventions to reduce carbon emissions in New Zealand. Science of the Total Environment 700, 134408–134408.

Independent Group of Scientists appointed by the Secretary-General, 2019. Global Sustainable Development Report 2019: The Future is Now - Science for Achieving Sustainable Development. United Nations, New York.

IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES Secretariat.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software 21, 602–614.

Kelle, U., Erzberger, C., 1999. Integration qualitativer und quantitativer Methoden. Kölner Zeitschrift für Soziologie und Sozialpsychologie 51, 509–531.

Klenert, D., Funke, F., Mattauch, L., O'Callaghan, B., 2020. Five Lessons from COVID-19 for Advancing Climate Change Mitigation. Environ Resource Econ 76, 751–778. https://doi.org/10.1007/s10640-020-00453-w

Le Blanc, D., 2015. Towards integration at last? The sustainable development goals as a network of targets. Sustainable Development 23, 176–187.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., Schellnhuber, H.J., 2019. Climate tipping points — too risky to bet against. Nature 575, 592–595. https://doi.org/10.1038/d41586-019-03595-0

Lusseau, D., Mancini, F., 2019. Income-based variation in Sustainable Development Goal interaction networks. Nature Sustainability 2, 242–247. https://doi.org/10.1038/s41893-019-0231-4

Mahoney, J., Goertz, G., 2006. A tale of two cultures: Contrasting quantitative and qualitative research. Political analysis 227–249.

Miola, A., Borchardt, S., Neher, F., Buscaglia, D., 2019. Interlinkages and policy coherence for the Sustainable Development Goals implementation. Joint Research Centre, Luxembourg.

Nugent, R., Bertram, M.Y., Jan, S., Niessen, L.W., Sassi, F., Jamison, D.T., Pier, E.G., Beaglehole, R., 2018. Investing in non-communicable disease prevention and

management to advance the Sustainable Development Goals. The Lancet 391, 2029–2035.
Ospina-Forero, L., Castañeda, G., Guerrero, O.A., 2020. Estimating networks of sustainable development goals. Information & Management 103342.
Pedercini, M., Arquitt, S., Collste, D., Herren, H., 2019. Harvesting synergy from sustainable development goal interactions. Proceedings of the National Academy of Sciences 116, 23021 LP – 23028. https://doi.org/10.1073/pnas.1817276116
Pedercini, M., Zuellich, G., Dianati, K., Arquitt, S., 2018. Toward achieving Sustainable Development Goals in Ivory Coast: Simulating pathways to sustainable development. Sustainable Development 26, 588–595. https://doi.org/10.1002/sd.1721
Posch, A., Scholz, R., Steiner, G., 2006. Integrating research and teaching on innovation for sustainable development. International Journal of Sustainability in Higher Education.
Sohl, T.L., Claggett, P.R., 2013. Clarity versus complexity: Land-use modeling as a practical tool for decision-makers. Journal of Environmental Management 129, 235–243.
Spash, C.L., 2020. 'The economy' as if people mattered: revisiting critiques of economic growth in a time of crisis. Globalizations 1–18. https://doi.org/10.1080/14747731.2020.1761612
Steffen, B., Egli, F., Pahle, M., Schmidt, T.S., 2020. Navigating the Clean Energy Transition in the COVID-19 Crisis. Joule 4, 1137–1141. https://doi.org/10.1016/j.joule.2020.04.011
Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J., 2018. Trajectories of the Earth System in the Anthropocene. Proc Natl Acad Sci USA 115, 8252–8259. https://doi.org/10.1073/pnas.1810141115
Stötter, J., Kromp-Kolb, H., Körfgen, A., Allerberger, F., Lindenthal, T., Glatz, I., Lang, R., Fehr, F., Bohunovsky, L., 2019. Österreichische Universitäten übernehmen Verantwortung. GAIA - Ecological Perspectives for Science and Society 28, 163–165.
United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015. (No. A/RES/70/1).
Vacik, H., Kurttila, M., Hujala, T., Khadka, C., Haara, A., Pykäläinen, J., Honkakoski, P., Wolfslehner, B., Tikkanen, J., 2014. Evaluating collaborative planning methods supporting programme-based planning in natural resource management. Journal of Environmental Management 144, 304–315.
Weitz, N., Carlsen, H., Nilsson, M., Skånberg, K., 2018. Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustainability science 13, 531–548.
Wiek, A., Withycombe, L., Redman, C.L., 2011. Key competencies in sustainability: a reference framework for academic program development. Sustainability science 6, 203–218.

8.1.1 Supplementary materials

8.1.1.1 Exemplary fact sheet

Method name	**Method cluster (optional)**	**Method approach**
Cross-impact matrix (CI-matrix)	Influence matrix	Argumentative
Current scope of application in the SDG context		
Global, regional, and country level; country-level recommended due to geographical differences in interactions (Nilsson et al., 2016); Assessment of interactions for different timescales recommended (Nilsson et al., 2016); Interactions within and between SDGs		
Short method description		
• The cross-impact matrix is a method designed for analyzing relationships between variables and factors. It can be used to analyze the relationship between SDGs as well as targets. The matrix elements of the cross-impact matrix contain numbers which describe how the occurrence of the row variable would affect the column variable. • Most often, expert judgements are used to assess the numbers, sometimes complemented by literature (e.g., Allen et al, 2019; Zaini and Akhtar, 2019). Numbers can also derive directly from literature on SDG interactions, such as the ICSU-ISSC report (Dawes, 2020). • Different scoring techniques can be applied. Most often, the seven-step scale proposed by Nilsson et al. (2016) with scores ranging from -3 (cancelling) to +3 (indivisible) is used (e.g., Allen et al, 2019, Weitz et al., 2018). Others apply binary scores (0 = no effect, 1 = effect) to arrive at a so-called 'reachability matrix' (Kumar et al., 2018; Zaini and Akhtar, 2019). Dawes (2020) aggregates scores for a single SDG based on the number of its targets' interlinkages to the targets of another SDG. • For further information and a more transparent research process, scores can be complemented with explanatory notes. This can also help foster discussions between the involved experts and/or authors of the respective study in order to adjust the scores (Weitz et al., 2018).		

8.1.1.2 Detailed description of the methods assessment for each method category

8.1.1.2.1 Argumentative methods

Argumentative methods allow considering expert knowledge in different ways. They performed similarly with regard to most criteria, with slight differences explained below. All argumentative methods fulfilled the effect criteria (c1-5), except for the Nilsson scale, which does not allow to display the direction of effects (c2) and thus feedback loops (c5). In the case of the Cross-impact matrix (CI matrix), context dependency was high ('4'), because various values, e.g., binary, positive numeric or positive and negative numeric, can be inserted, which may or may not display polarity (c3) and degree (c4) of effects as well as feedbacks (c5).

The inclusion of qualitative (c6) and quantitative (c7) information is possible for all argumentative methods. For expert elicitation, the inclusion of quantitative data is highly dependent on the context (‘4’), as this applies only if the elicited experts perform a quantitative assessment themselves, rather than having their qualitative assessments quantified. Implicit knowledge can be included when applying argumentative methods, except for the CI matrix, which can only process explicit information. As with most of the reviewed methods, the consideration of subjective preferences (c9) is not possible, except in expert elicitation. However, this assessment had a relatively high context dependency (‘3”) since it depends on how the questions in the elicitation are asked.

Argumentative methods can all be used in collaborative settings (c10) as well as in large groups (c11), but depending on the context, this might not necessarily make much sense in practice (relatively high context dependencies = ‘3’). This pertains particularly to expert elicitation as the method ranges from one-time surveys to several-round workshops. Although it is quite context-dependent (‘3’ or ‘4’), it is assumed that the use of argumentative methods generally increases the system understanding of involved experts (c12) as these methods allow drawing inferences on complex SDG entity interactions. Seeing that the Nilsson scale does not display the direction of effects and thus feedbacks, it did not fulfil this criterion.

Information on the certainty of results (c13) is a key element of Bayesian belief networks (BBN) and can also be included in expert elicitation, when specifically asked for (high context dependency = ‘4’). Even though one could possibly conceive ways of incorporating certainty measures into Causal loop diagrams (CLD) and the Nilsson scale, however no examples where find where this has been attempted. With the CI matrix, such information cannot be included. Generally, all argumentative methods operate transparently (c14). The interpretation of results (c15) is quite intuitive and thus easy for the Nilsson scale and almost all conceivable use cases of the CI matrix. For BBN and CLD this strongly depends on how results are processed, i.e. the complexity of the illustration, as well as the complexity of the topic and the know-how of the user. Results from expert elicitation might not be well structured in some cases and therefore more difficult to interpret. All argumentative methods can be adapted to different scales (c16), although this may pose additional challenges for expert elicitation with regards to the selection of experts (indicated through a relatively high context dependency =

‘3’). The application of BBN and CLD requires specialized methodological knowledge (c17). This also holds true for expert elicitation, but the latter is more dependent on the specific process of elicitation (‘3’). Neither the CI matrix nor the Nilsson scale require specialized knowledge for application. Computer-based support (c18) is a necessity for using BBN (otherwise not feasible). Both CLD and CI matrix might require it in particular cases (e.g., large amounts of data), but not per se (relatively high context dependency = ‘3’). The time effort is high for those argumentative methods that involve experts (BBN = 4, CLD = 3, expert elicitation = 4), but not as high for the CI matrix and the Nilsson scale. For expert elicitation, this is highly context-dependent (‘4’), as the method ranges from one-time surveys to several-round workshops.

8.1.1.2.2 Literature methods

Literature methods can help to draw a comprehensive picture of a certain topic and, depending on the available literature, pose a relatively simple, even if possibly time intensive, method for many different settings. They can be used as sole method within a paper or in combination with, as a baseline for or for complementation of other methods (e.g., with an Accounting framework (Engström et al., 2018), scoring with Nilsson scale and Structured elicitation of expert information (Hazarika and Jandl, 2019), or with a Keyword analysis (De Paiva Serôa Da Motta, 2019)).

For most of the criteria the literature methods showed similar performances. The effect criteria (c1-c5) were fulfilled by all methods. For c4 and c5, however, context dependency was high, as the ability to detect the degree of an effect and feedback loops depends on the content of the literature analyzed.

Inclusion of qualitative information (c6) is possible, as the input information (the available literature) is regarded as qualitative data. The criteria for inclusion of quantitative information (c7) was defined not to be fulfilled as quantitative data needs to be embedded in the text to be used in literature methods. Any inclusion of quantitative information would require raw data in numerical form. Retrieved from existing studies, this would be regarded as a meta-analysis and, depending on the method used, allocated to another approach category. Literature methods do not allow to include implicit information (c8), as input information is limited to published material and implicit information as defined in the criterion description (see table A.1) is regarded as knowledge that is not documented. Systematic literature reviews do not allow considering subjective preferences (c9) except for some space for interpretation. For the other three literature methods preferences can be reflected in the selection of analyzed literature and interpretation.

Publications using literature methods exclusively do not encourage their use in a collaborative setting (c10). However, the representation of various disciplines and perspectives can be of advantage. Literature methods can be applied in a big group (c11), e.g., by dividing the work. Depending on the search systematics and the literature sources system understanding of the involved experts (c12) can be increased through the application of the method, when new perspectives are gained and included in the analysis.

In terms of the certainty of the results (c13), the literature methods differed from each other. In most cases of Systematic literature reviews, information about certainty of the results (c13) can be included discussing agreement on a topic in a descriptive way within the assessed literature. In Semi-systematic and Non-systematic literature reviews as well as Reviews of case studies it can mostly not be included, as the literature is rather limited and, in most cases, not exhaustive. All of the literature methods should be transparent (c14), but the level of systematics and reproducibility can be comparatively low for Semi-systematic and Non-systematic literature reviews and Review of case studies depending on the actual implementation of the methods. Literature methods produce texts already including interpretation of results and therefore their output is per se easy to interpret (c15). Furthermore, the reviews can be supported by illustrations or tables, which facilitates their interpretability.

Depending on the available literature, all methods in this category can be adapted to different scales (c16). Time effort (c19) is relatively high (‘3’), compared to most other methods, but highly depends on the degree of specification of the search string, the level of scientific coverage of the topic as well as expertise and experience of the authors concerning the topic. When case studies are used, the authors might have previous knowledge of the literature as often they are familiar with the assessed case studies. Other than that, literature methods are quite easily manageable as a low level of specialized knowledge is needed (c17) and they do not require computer-based support (c18), apart from the possible use of a literature search tool, which was not considered as a special software.

8.1.1.2.3 Linguistic methods

The approach category 'Linguistic' only includes one method, Keyword analysis (KWA). Regarding effect criteria (c1-c5), the method performed quite mixed. It allows detecting effects (c1) with their degrees of expression (c4), which can easily be measured by the number of occurrences of certain keywords. However, assessing the degree of effects is not a standard procedure, but strongly depends on the type of application and therefore exhibited an increased context dependency ('3'). Since the method's approach is based on wording similarities in text documents, it fails to take into account the direction of an effect (c2) and its polarity (c3) and thus is unable to represent feedback loops (c5).

In terms of interdisciplinary sensitivity KWA was assessed as rather unsuitable. It does not allow the inclusion of quantitative or implicit information (c7, c8), since analysis is based on documents and thus qualitative information (c6).

Concerning collaboration criteria KWA was rated as rarely applicable (c10-c13). It cannot be used collaboratively (c10) and its application is not suited for larger groups (c11). Similarly, it does not increase system understanding (c12).

Practicability criteria were fulfilled quite well (c13-c19). The method does not give information about the certainty of results (c13), but operates transparently (c14), as method procedures are clearly described and reproducible. The obtained results are easy to interpret (c15) and, depending on available documents, the method theoretically can be adapted to various scales (c16). The effort required for this method was rated as very feasible. The time effort needed (c19) is relatively low compared to other methods, there is no specialized methodological knowledge (c17) and also no computer-based support necessarily required (c18). Whereby computer-based support could even reduce the time required.

8.1.1.2.4 Simulation methods

Most simulation methods performed similarly across the criteria. Since most model simulations are emulations of real-world processes (and thus interactions) they met almost all effect criteria (c1-c5). However, some simulation methods can display feedback loops (c5) only to certain degrees with high context dependency, i.e., Computable general equilibrium models (CGE), Energy system models (ESM), and Integrated assessment models (IAM).

While all simulation methods require quantitative information (c7), they are not able to process qualitative (c6) or implicit information (c8), unless these are transformed into quantitative numbers (the criteria require a direct usage without quantifying this information). Hence, to fully utilize such methods for inter- and transdisciplinary research, intermediate methods for knowledge co-creation and quantification of qualitative and implicit information have to be applied. All simulation methods allow, from a technical point of view, the incorporation of subjective preferences (c9). This can be done by incorporating constraints (e.g., a maximum greenhouse gas budget) or multi-objective programming methods (with different weights for different goals) into simulation models. However, many simulation models are, by default, economic optimization models, i.e., they minimize costs or maximize some welfare criterion.

Most simulations are created in a collaborative setting (c10), as most simulation models require a team of experts to maintain and operate it. This is especially the case for IAMs, where different disciplinary models are linked. IAM is also the only simulation method which therefore does not only allow but may even require the application in a big group (c11). The possibility of applying the other methods in large groups appears to be very limited, but this may change, depending on the context. All simulation methods may substantially improve the system understanding of involved experts (c12, especially in potentially interdisciplinary methods, such as Agent based modelling (ABM), IAM and System dynamics modelling (SD).

Practicability criteria were evaluated to be very context dependent for simulation models. In theory, every simulation is able to provide information on the certainty of results (c13) and, according to good conducts in modelling (Jakeman et al., 2006), should do so. However, due to their computational burden this is probably less applied in IAMs. Transparency (c14) crucially depends on individual simulation models and not generic methods per se, so this could not be judged based on method level. Again, this should be part of any good conduct in modelling (Gabbert et al., 2010). A disadvantage of large simulation models, such as IAMs, is the difficulty of understanding such models even under full transparency and the lack of replicability of results by individual researchers (Sohl and Claggett, 2013). A technical disadvantage of simulation models is that almost all models provide raw output (activity) data that is difficult to interpret (c15) unless these activity data are processed into more understandable indicators, formats and/or visualizations. The interpretability (c15) is also linked to the understanding of the applied model algorithms and hence depends on a transparent documentation of the model (c14). Adaptation to different scales (c16) is a difficult criterion to assess for simulation methods, as it highly depends on the context: Is the data available at different scales? Are interactions between different scales considered in the model? In theory, most models may be adapted to different scales. In practice, however, this will often entail major difficulties, especially if processes behave differently at different scales. Almost all simulations require substantial time effort (c19), which is likely the highest among all method categories, even with the underlying assumption that a core simulation model is available to the researchers. This also highlights that quantitative whole-system approaches may require substantial time efforts, as IAMs (which often consist of interlinkages between the other simulation methods) ranked highest in time effort needed among the simulation methods. All methods require specialized knowledge of the methods (c17) and computer-based support (c18) is essential. Overall, they were thus evaluated to have high management efforts.

8.1.1.2.5 Statistical methods

The statistical methods had very similar assessment results across the different methods within this group. The results for the effect criteria were rather positive, but still weak in comparison to other method groups. Most of the methods are not able to detect the direction of effects (c2) except for the Cox proportional hazards models (CPH), Generalized method of moments (GMM), and Pairwise granger causality test (PGC). None of the methods can detect feedback loops (c5).

Also, the interdisciplinarity sensitivity criteria (c6-c9) did not perform very well in comparison to other method groups, since only quantitative information can be included into the examined statistical methods. Qualitative and implicit information would have to be converted, a step which only was considered in the assessment when part of the method.

Furthermore, statistical methods showed very low achievement of collaboration criteria (c10-c12). None of them can either be used in a collaborative setting or big group, nor does the application of the method itself enhance system understanding of the person or people applying the method.

However, when it comes to practicability criteria fulfilment was relatively high. In particular, the interpretability of results (c15) and adaptability to different scales (c16) is existent for all statistical methods. Although, the scalability of a method slightly depends on the context, e.g., the availability of data. Except for Descriptive statistics and Advanced sustainability analysis (ASA), all statistical methods give information about the certainty of results (c13), e.g., through standard errors. ASA was also the only statistical method (and the only method at all) that was assessed not to operate fully transparently (c14), because results are dependent on deltas between start and end dates and time series in between are not considered.

The time effort (c19) was estimated to be comparably low ('2') for all statistical methods, however, with varying degrees of context dependency. For all methods the time effort was assessed to have a slightly increased context dependency, due to possible data availability and data quality issues. The remaining manageable efforts criteria (c17, c18) however, performed rather badly, since computer-based support and expert knowledge is required in all statistical methods but Descriptive statistics, which does not require much specialized knowledge, due to very basic and easy calculations.

In general, the context dependency of the assessments for this approach category was very low. Slightly increased context dependencies were limited to certain criteria (scalability, c16 and time effort, c19) and based on possible data availability and data quality issues.

8.1.1.2.6 Other quantitative methods

The assessment results for the remaining quantitative methods did not differ very much from the results of the statistical methods. However, in contrast to all statistical methods and the other methods in this group (other quantitative methods) Network analysis (NWA) allows detecting feedback loops (c5). As a precondition for this trait, NWA also allows detecting the direction of effects (c2), which is also true for Environmentally-extended multi-regional input-output models (IO).

The collaboration criteria were not fulfilled for the whole group, except for NWA and IO, which can increase system understanding (c12).

Speaking of practicability criteria, unlike most statistical methods and all simulation methods, NWA and the Accounting framework (Account) do not give information about the certainty of results (c13). Models such as IO should do so. However, IO models are, at core, basically empirical balance sheets of money and biophysical flows and therefore c13 is probably less applied in IO modelling, wherefore the context dependency was assessed quite high here ('4'). For NWA and IO transparency (c14) could not be assessed on a method level, because it highly depends on the application and the individual model used. Regarding the interpretability (c15) IO models were more similar to methods in the simulation group, with the same issue of raw data output. Scalability (c16) was assessed similar to statistical methods for this group ('true') with a higher context dependency for IO ('3'), due to specific model adaptability issues (such as indicated above in section 'Simulation methods').

While, similar to the statistical methods, time effort (c19) was assessed relatively low ('2'), computer-based support (c18) is needed for all 'other quantitative methods'. Also, specialization requirements are quite high, with all methods but accounting frameworks requiring specialized knowledge of methodology (c17). In general, the context dependency of the assessments was again very low in this group.

8.2 Publication II

Received: 23 February 2017 | Revised: 10 May 2018 | Accepted: 21 June 2018

DOI: 10.1002/mcda.1648

RESEARCH ARTICLE

WILEY

A comprehensive uncertainty analysis of the analytic hierarchy process methodology applied in the context of environmental decision making

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Funding information
BOKU Vienna Open Access Publishing Fund; University of Natural Resources and Life Sciences, Vienna

Abstract

An overview of uncertainty issues associated with the analytic hierarchy process (AHP) is provided. Further, an explicit understanding of uncertainty (designation, categorization, and quantification) with respect to the methodological properties of the AHP is developed and used to analyse a hypothetical group decision problem located in the context of environmental decision making (EDM). To calculate the numerical impact of especially designed uncertainty scenarios (USs) on the final ranking given by the AHP, a simulation experiment is conducted using R. It evaluates the impact of uncertainty within three variants of a hypothetical decision-making case by calculating an "overall uncertainty" measure. The consideration of uncertainty may lead to a rank reversal in comparison with that analysis neglecting uncertainty (best alternative given by the AHP). The results show that the absolute maximal impact caused by a US is approximately 0.03. With respect to a single US and the specific case characteristics, in about 50% of the simulated runs a rank reversal occurs. Similar shares of rank reversal over different USs within a single variant of the case raise the question to which uncertainty should be given prior attention in decision-making practice. For decision analysts in EDM, this result implies that additional resources may be necessary to commonly negotiate with decision makers that uncertainties should be addressed. From a theoretical normative point of view, the effects of considering uncertainty issues in the AHP methodology cannot satisfy the ideal of a rational decision analysis. From a descriptive point of view, considering the practice of decision makers, the impacts of the considered uncertainties stay within reasonable limits, meaning that the maximal numerical impact stays on the hundredths decimal place.

KEYWORDS

designation, categorization, and quantification of uncertainty, overall uncertainty measure, scenarios, simulation experiment, uncertainty modelling

1 | INTRODUCTION

1.1 | Environmental decision making

The arising global environmental change is going to lead to undesired and irreversible consequences for large parts of the world (Rockstrom et al., 2009). Considering a transformation to a sustainable development is therefore inevitable. Environmental decision making (EDM) supports this transformation in guiding the selection between different choices. EDM is seen in quite general terms, that is, "environmental decisions are those choices or judgements that have a significant impact on the environment" (Harding, Hendriks, & Faruqi, 2009, p. 4). The understanding of the term environment may vary (Scholz & Binder, 2011). Here, a broad understanding including all dimensions (biophysical, social, economic, and political) that define our surroundings is used (Harding et al., 2009). Basically, EDM has to cope with a tremendous complexity arising from human–environment interaction. Environmental decisions are multifaceted and often involve several stakeholders with different objectives that cannot be satisfied simultaneously. Furthermore, EDM typically uses knowledge from several disciplines incorporating natural, physical, and social sciences as well as medicine, politics, and ethics. EDM is located in the normative context of sustainable development and aims to trade off the three dimensions of sustainability (Ecological, Social, and Economical). In other words, decision making regarding the environment is concerned with solving "sustainability problems" (Harding et al., 2009). Dovers (2005) identifies several characteristics of such problems, for example:

- extended temporal and spatial scales of impacts in natural systems
- complex connections between issues, especially natural phenomena are linked in cause or consequence
- high level of uncertainty of consequences of human intervention in natural systems and poor quality information about state of natural systems
- need for community participation

Multicriteria decision making (MCDM) methods are often used to structure and solve environmental decision problems involving multiple stakeholders, objectives, and alternatives. In the process of making environmental decisions, important information may be lost, competing values may be discarded, and elements of uncertainty may be ignored. Hence, many environmental decisions bring along unintended consequences that are not reflected in the decision-making process (Dietz, 2003; Harding et al., 2009; Kiker, Bridges, Varghese, Seager, & Linkov, 2005; Scholz & Binder, 2011). Ascough Ii, Maier, Ravalico, and Strudley (2008) identify the fundamental need to further develop knowledge related to the incorporation of uncertainty issues in EDM. Since its inception, the original analytic hierarchy process (AHP) using the exact method and an additive aggregation mode (Saaty, 1995) has been extensively used in EDM and natural resource management (Cinelli, Coles, & Kirwan, 2014; Reichert, Langhans, Lienert, & Schuwirth, 2015; Schmoldt, 2001; Vacik et al., 2014; Vacik & Lexer, 2001). Sometimes, the final results of an evaluation do not allow decision makers to select the preferred alternative, as they might question the robustness of the results or the related assumptions (Wolfslehner & Vacik, 2011). Recent studies investigate the need for addressing uncertainty issues of the AHP (Cinelli et al., 2014; Vacik et al., 2014). More specifically, literature reveals a wide range of theoretical reflections, simulation experiments, and procedural modifications of the AHP (e.g., Hung, Ma, & Yang, 2009; Ishizaka & Nemery, 2013; Levary & Wan, 1998; Ozdemir & Saaty, 2006; Paulson & Zahir, 1995; Saaty, 2010; Sadiq & Tesfamariam, 2009; Warren, 2004; Wolfslehner, Vacik, & Lexer, 2005). The authors are concerned about methodological properties of the AHP that can cause "uncertainty" regarding the derived results. The term "uncertainty" is understood here in a very general way, referring to methodological "knowledge gaps or ambiguities that affect our ability to understand the consequences of decisions" recommended by the AHP (Gregory et al., 2012, p. 127). We use the term "uncertainty issue" here to capture these methodological properties. A systematic overview of these widely discussed but scattered properties is missing. Several authors indicate that in most application studies, these embedded properties are not sufficiently acknowledged (Hung et al., 2009; Warren, 2004).

Nevertheless, some of the publications investigating uncertainty issues show a reasonable systematic examination of uncertainty issues involved, that is, a cross-sectional view along the different steps of MCDM (Belton & Stewart, 2002), but an explicitly formulated understanding of uncertainty is missing. For example, Sadiq and Tesfamariam (2009) apply an extended AHP methodology to handle both vagueness and ambiguity as types of uncertainty in EDM. Also, the recently published overview "In the black box of AHP" (Ishizaka & Nemery, 2013) summarizes various uncertainty issues.

Hence, to foster the understanding of the fundamentals of the AHP, the overall aims of this paper are (a) to provide a systematic overview of the uncertainty issues discussed in scientific literature, (b) to present a procedure of a comprehensive uncertainty analysis of the AHP, and (c) to analyse the uncertainty involved in a case study of EDM. The paper is organized as follows: After a general overview about the uncertainty issues related to the AHP, Section 2 outlines three dimensions of an explicitly formulated understanding of uncertainty. In Section 3, a procedure of a comprehensive uncertainty analysis is presented and applied in Section 4. After the combined presentation of results and discussion in Section 5, conclusions are drawn in Section 6.

1.2 | Overview of uncertainty issues associated with the AHP

Table 1 summarizes 12 major uncertainty issues associated with the usage of the AHP and allocates them to the four different steps of MCDM (Belton & Stewart, 2002) considering group decision making as well. From the short summaries provided for each identified uncertainty issue, it becomes evident that a lot of meta-choices have to be made to solve a decision problem, whereas the involved human judgements are subject to numerous cognitive and motivational biases (Ferretti & Montibeller, 2016; Montibeller & von Winterfeldt, 2015). For example, the AHP user has to choose which scale presentation mode (verbal or numeric) appears to be more suitable for eliciting judgements. Hence, the way how human inputs are incorporated in

TABLE 1 Overview of uncertainty issues associated with the AHP

Steps of MCDM	Embedded uncertainty issues
Problem modelling	Uncertainty associated with modelling—General inability of models to represent the problem it attempts to structure (Maier, Ascough, Wattenbach, Renschler, & Labiosa, 2008) Uncertainty associated with the development of the model structure—Determination of structure of an numerical, hierarchical induction model; how to include which elements (e.g., criteria/subcriteria, "wash criteria," or "future aspects") to capture the real-world complexities? (Brugha, 1998, 2004; Finan & Hurley, 2002; Levary & Wan, 1998; Maleki & Zahir, 2013; Saaty, 2007; Saaty & Begicevic, 2010; Warren, 2006) Uncertainty associated with the incorporation of important, but "unknown" factors—How to include important, but only suspected and not explicitly articulated factors into the problem modelling? (Ozdemir & Saaty, 2006)
Weights valuation	Measurement theoretical debate—Is the original preference measurement scale (linear; Saaty scale) a ratio scale? (Barzilai, 2001, 2006; Bernasconi, Choirat, & Seri, 2010, 2011; Salo & Hämäläinen, 1997) Uncertainty associated with the used scale type—Which scale (e.g., linear [Saaty scale], power, or logarithmic) is used to elicit the pairwise comparisons? Should the used scale be adapted to the individual decision makers' characteristic? (Beynon, 2002a; Choo & Wedley, 2010; Dong, Hong, Xu, & Yu, 2013; Dong, Xu, Li, & Dai, 2008; Finan & Hurley, 1999; Harker, 1987a; Leskinen, 2001; Liang, Wang, Hua, & Zhang, 2008; Saaty & Ozdemir, 2003) Uncertainty associated with the response mode—Which scale presentation mode (e.g., verbal or numeric) is used to elicit the pairwise comparisons from the decision makers? (Huizingh & Vrolijk, 1997; Pöyhönen, Hämäläinen, & Salo, 1997; Webber, Apostolou, & Hassell, 1997) Uncertainty associated with vague judgements—How (e.g., interval judgements or fuzzy set theory) to incorporate the imprecision of human judgement into the process? (Deng, 1999; Leung & Cao, 2000; Mikhailov, 2004a; Moreno-Jimenez & Vargas, 1993; Saaty & Tran, 2007; Sadiq & Tesfamariam, 2009; Sugihara & Tanaka, 2001; Zhü, 2014) Uncertainty associated with incomplete pairwise comparison matrices—How to deal (e.g., Monte Carlo simulation approaches or optimization methods) with incomplete pairwise comparison matrices? (Bozóki et al., 2010; Carmone, Kara, & Zanakis, 1997; Fedrizzi & Giove, 2007; Harker, 1987b; Hua, Gong, & Xu, 2008; Kwiesielewicz & Van Uden, 2003; Srdjevic et al., 2014; Wedley, 1993) Uncertainty associated with consistency measurement—How to check (e.g., usage of which random indices?) that the provided decision makers' judgments are logical, reasonable, and nonrandom? In the case the judgements appear random, what kinds of modifications are feasible? How to ensure group consistency? (Cao, Leung, & Law, 2008; Dadkhah & Zahedi, 1993; Dodd, Donegan, & McMaster, 1993; Donegan & Dodd, 1991; Grošelj & Stirn, 2012; Ishizaka & Lusti, 2004; Karapetrovic & Rosenbloom, 1999; Kwiesielewicz & van Uden, 2004; Lamata & Alonso, 2006; Moreno-Jiménez et al., 2008; Ramík & Korviny, 2010; Zeshui & Cuiping, 1999) Uncertainty associated with priority derivation—How (e.g., synthesis mode, normalization procedure, and the issue of rank preservation and reversal) to derive preference values from the pairwise comparison matrices? Does the eigenvalue method is sufficient to derive priority? (Bana e Costa & Vansnick, 2008; Barzilai & Golany, 1994; Belton & Gear, 1983; Belton & Gear, 1985; Choo & Wedley, 2004; Dyer, 1990; Harker & Vargas, 1990; Holder, 1990; Hung et al., 2009; Huo, Lan, & Wang, 2011; Ishizaka & Labib, 2011a; Ishizaka & Lusti, 2006; Johnson, Beine, & Wang, 1979; Maleki & Zahir, 2013; Millet & Saaty, 2000; Saaty & Vargas, 1984; Saaty & Vargas, 1993; Triantaphyllou, 2001)
Weights aggregation	Uncertainty associated with the aggregation mode between the different levels of the problem modelling hierarchy—How (additive or multiplicative) to aggregate preferences to an overall preference vector? (Choo, Schoner, & Wedley, 1999; Stam & Duarte Silva, 2003; Triantaphyllou, 2001)
Sensitivity analysis	Uncertainty associated with the type of sensitivity analysis—how (e.g., variation in judgements or one-/multidimensional simulation approaches) to conduct an appropriate sensitivity analysis? (Butler et al., 1997; Chen & Kocaoglu, 2008; May, Shang, Tjader, & Vargas, 2013; Triantaphyllou & Sanchez, 1997)
Group decision making	Uncertainty associated with the combination procedure of several decision makers' judgments—How (e.g., geometric mean on pairwise comparisons, weighted arithmetic mean on derived priorities, or consensus models) to derive an appropriate group aggregation? (Altuzarra et al., 2007; Dong et al., 2010; Forman & Peniwati, 1998; Grošelj et al., 2015; Ishizaka & Labib, 2011a; Mikhailov, 2004b; Ossadnik et al., 2016; Saaty & Peniwati, 2013; Saaty & Vargas, 2012)

Note. AHP: analytic hierarchy process; MCDM: multicriteria decision making.

the process of decision making has to be considered carefully in EDM (Ascough Ii et al., 2008; Hämäläinen, 2015; Hofmann, 2007).

2 | THREE DIMENSIONS OF UNCERTAINTY

The understanding and definitions of "uncertainty" vary according to the scientific disciplines, practice areas, and problem approaches (Bammer & Smithson, 2008). As an explicitly formulated conceptualization of uncertainty involved in applying the AHP is missing, such an approach was presented at the International Symposium of the AHP 2014 (Toth, Wolfslehner, & Vacik, 2014). The proposed understanding of uncertainty is primarily based on Walker et al. (2003) who provide a conceptual basis for the systematic treatment of uncertainty in model-based decision support. Although this publication received some criticism (Norton, Brown, & Mysiak, 2006), it seems meaningful to use its conceptual basis and to adopt it to the conceptual needs of the AHP. In this context, three dimensions of uncertainty, namely, designation (see Section 2.1), categorization (see Section 2.2), and quantification (see Section 2.3), are proposed.

2.1 | Designation of uncertainty

The designation is aimed to give a first idea what the specific uncertainty is about and seeks to find a representative name as relation of the linguistic level to the conceptual level (Bunge, 1967). It supports communication, documentation, and comparison of identified uncertainties.

2.2 | Categorization of uncertainty

The categorization clarifies where the specific uncertainty is located in the procedure of the AHP and which type and nature of uncertainty can be specified. Walker et al. (2003) distinguish between three dimensions of uncertainty, which can be linked to the AHP:

Dimension (i) The location of uncertainty refers to the procedure and aims to identify the location within the model where the uncertainty is generated. For this, the five generic locations "Context," "Model structure uncertainty," "Model technical uncertainty," "System data," and "Parameter uncertainty" are identified:

Context refers to the question where to identify the boundaries of the decision problem to be modelled. In the context of EDM, the choice of boundaries is often a matter of negotiation. In other words, the various stakeholders involved have to develop a mutual problem understanding of included alternatives and criteria, which then can be transformed into a specific AHP model.

Model structure uncertainty involves "uncertainty associated with the relationships between inputs and variables, among variables, and between variables and output, and pertains to the system boundary, functional forms, definitions of variables and parameters, equations, assumptions and mathematical algorithms" (Walker et al., 2003, p. 10), indicating that all intermediate calculations—steps such as priority derivation from a pairwise comparison matrix, the used aggregation procedure of the local alternative priorities, or the group aggregation method of the AHP—may embed uncertainties.

Model technical uncertainty refers to errors generated by the computer implementation of the model. Especially software and hardware errors are relevant in this context but are neglected in this contribution. Following the categorization by Walker et al. (2003), "external driving forces" are uncontrollable and produce changes within the system whereas system data embraces datasets describing elements of the relevant problem. The proposed uncertainty levels by Walker et al. are oriented on models that try to represent natural, economic, and social systems. According to our interpretation and in line with Warren (2006), we interpret the AHP not as a representation of such a system, rather as an "information aggregation technique" supporting the decision makers in representing relationships between the real world objects of the relevant problem. Hence, only system data seems to be reasonable to be included.

Parameter uncertainty is associated with the use of constants within the model. The certainty regarding different parameters may vary between absolute certain (e.g., gravitational constant) and less certain due to the necessity to choose a priori or to calibrate the level of the parameters. The calculation of the consistency ratio of the AHP relies on a random index, which itself was due to statistical fluctuations recalculated over time (Saaty, 1996).

Dimension (ii) The level of uncertainty gives an idea about the type of uncertainty and is associated with different levels of knowledge. The AHP is an "information aggregation technique" that includes subjective pairwise comparisons. In this context, Sadiq and Tesfamariam (2009) assign "vagueness" and "ambiguity" as possible classifications to different steps of the AHP. The basic feature of Dimension (ii) is the consideration of a one-to-many relationship, where the decision maker is uncertain which possibility to choose (Toth, 1999). According to Klir and Yuan (1995), vagueness is understood as the result of the lack of sharpness of relevant distinctions, which leads to situations in which different interpretations are possible (Zhang, 1998). Ambiguity is linked to discord, which indicates any situation in which it remains unclear which of several alternatives should be accepted as the genuine one (Klir & Yuan, 1995). In reference to the AHP, one question is related to incomplete pairwise comparison matrices, where it has to be decided how to express the decision maker's lack of knowledge. A genuine procedure to complete the missing information has not been developed yet; hence, a procedure has to be chosen.

Dimension (iii) The nature of uncertainty allows another classification; it clarifies whether the uncertainty is due to the imperfection of our knowledge (epistemic uncertainty) or if it is due to an inherent variability (variability uncertainty) of the phenomenon involved. Epistemic uncertainty is according to Walker et al. (2003) related to many aspects of modelling (e.g., limited and inaccurate data, measurement error, incomplete knowledge, limited understanding, imperfect models, subjective judgement, and ambiguities). Variability uncertainty has to do with empirical quantities that vary over space and time and is defined as inherent uncertainty or randomness

TABLE 2 Possible classifications of an uncertainty with respect to three categories

Categories					
Generic location	Context	Model structure uncertainty	Model technical uncertainty	System data	Parameter uncertainty
Type	Vagueness	Ambiguity			
Nature	Epistemic	Variability			

induced by variation associated with external input data, input functions, parameters, and certain model structures (Walker et al., 2003).

It is a challenge to distinguish the identified uncertainties' dimensions and to establish a distinct classification for each of them. Table 2 shows the overview of all possible classifications of an uncertainty related to the three categories generic location, type, and nature introduced. However, according to our interpretation also, an allocation of various characterizing attributes to a single uncertainty seems appropriate to provide a profound description.

2.3 | Quantification of uncertainty

The quantification analyses the numerical impact of uncertainty on the final alternative ranking given by the AHP. For this purpose, it is necessary to focus on the basic algorithms of the AHP, because widely used software products do not allow considering uncertainty issues as listed in Table 1.

3 | PROCEDURE FOR A COMPREHENSIVE UNCERTAINTY ANALYSIS

The procedure is based on the three proposed dimensions of uncertainty and allows the analysis of the involved uncertainty regarding a specific decision problem in EDM (Figure 1).

1. The procedure starts with the elaboration of an in-depth analysis of the decision problem. This is done by building the decision hierarchy used in the AHP, collecting available data and its embedded assumptions, and clarifying the system boundaries to be modelled. Additionally, the fundamental characteristics of the decision problem are elaborated in the sense of common properties in the specific context. This helps to reveal the linkages of the decision problem with the uncertainty causing methodological properties of the AHP as shown in Table 1.
2. Based on this in-depth analysis, uncertainties involved can be identified. The relevance and kind of uncertainties may vary among different application areas such as EDM or technical engineering.
3. Subsequently, the identified uncertainties are designated and classified with respect to the provided categories given in Table 2.
4. The quantification of uncertainty involves the construction of uncertainty scenarios (USs) that capture all possible combinations of the identified uncertainties.
5. Based on literature research and/or expert judgements, a numerical formulation of these uncertainties should be established.

6–7. For completion of the quantification, a simulation experiment is conducted. It includes programming of the AHP accompanied by the implementation of the decision problem and a numerical implementation of the constructed USs.

8. The synthesis allows to measure "overall uncertainty," that is, to test the numerical impact of the identified uncertainties on the final alternative ranking involved in the decision problem under consideration.

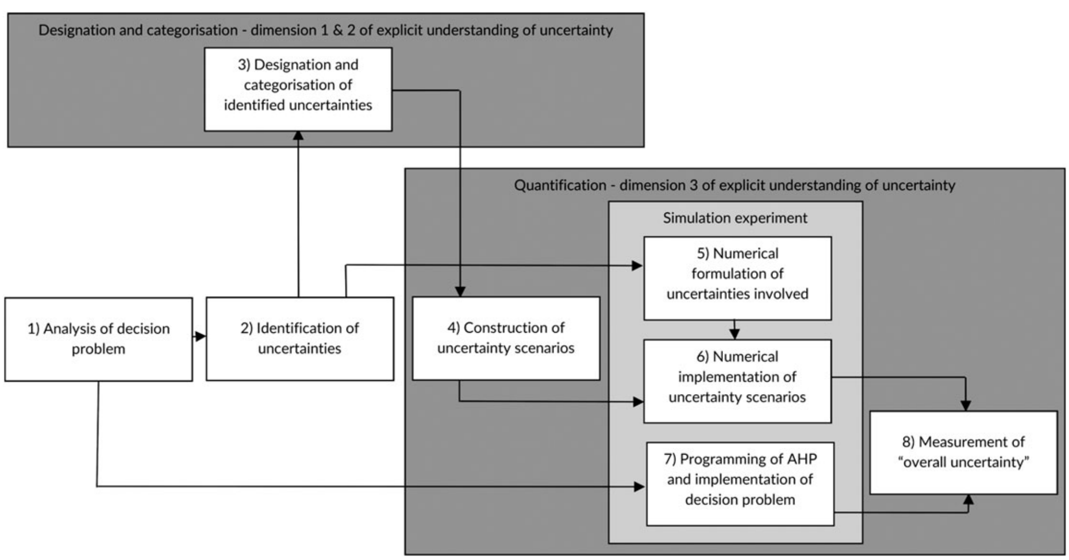

FIGURE 1 Scheme of procedure of a comprehensive uncertainty analysis

4 | APPLICATION OF THE COMPREHENSIVE UNCERTAINTY ANALYSIS PROCEDURE

4.1 | Analysis of the decision problem

4.1.1 | Decision hierarchy

The hypothetical decision problem is about making a choice regarding a new purchase of a heating system for a one family house located in Vienna, Austria. Several assumptions and some simplifications had to be made to manage the programming effort of a cross-sectional view of uncertainty issues along the different steps of MCDM.

A family consisting of the parents (father and mother) and two children (adolescents) wants to mutually decide on this purchase problem. Guidelines and information material usually present a broad range of possible alternatives (Cerveny & Sturm, 2012; Federal Environment Agency, 2001). After consulting guidelines provided by local authorities (Huber, Schöfmann, & Zottl, 2014), it becomes clear that due to the specificity of the piece of ground, any heating system using terrestrial heat is not compatible with current law. Also, combinations of different technologies are technically possible, but neglected here. Furthermore, it is decided to neglect any coal heating system, because of its massive environmental impact. As a result, the alternatives "Logs," "Wood pellets," "Natural gas," and "Oil" are considered in the purchase decision. The family anticipated this environmental decision problem as a "sustainability problem"; hence, it is tried to trade off the three dimensions of sustainability (Ecological, Social, and Economical). For this purpose, the balanced set of criteria "Costs," "CO_2 emissions," "Feeling of security," and "Security of resource supply" is used. Of course, a further decomposition (e.g., including subcriteria under Costs) could be performed or more criteria (e.g., "Environmental impact of resource exploitation") could be considered. However, for the purpose of this case study, the family's problem formulation phase resulted in a three-level decision hierarchy (Figure 2).

Two of the included criteria (Costs and CO_2 emissions) are a matter of gathering quantified data, and the other two (Feeling of security and Security of resource supply) are a matter of qualitative evaluation (Table 3).

The alternatives' performance under the criterion Costs represents life cycle costs. The data are related to an assumed heating energy consumption of 30,000 kWh per year (corresponds to a living area of about 180 m^2; E-Control, 2004) and to an assumed constant average price level for different energy sources for 20 years (Cerveny & Sturm, 2012). The alternatives' performance under the criterion CO_2 emissions also embeds a life cycle view and includes the emissions produced throughout the life cycle of a specific energy source (Federal Environment Agency, 2001). The alternatives' performance under the criteria Feeling of security and Security of resource supply is a matter of qualitative evaluation (see Section 4.3.1). Feeling of security refers to eventual carbon monoxide emissions from a boiler or complications in a fireproof wood pellets heating room. Security of resource supply, for example, has to do with the perception of frictions between Russia and Ukraine and the related natural gas dependency of Austria.

4.1.2 | Three variants regarding preference tendency

As the involved individuals of the family may express coincidental preferences or more conflicting ones, three variants of the proposed decision problem are considered:

Variant I is based on the assumption that the preferences follow specific stereotypes (compare with Section 4.3.1).

Variant II captures an extreme constellation of the involved preferences and aims to foster the performances included in the used quantitative data (Table 3; compare with Section 4.3.1).

Variant III is based on the assumption that all family members express maximal diverging preferences within each qualitative evaluation (compare with Section 4.3.1).

4.2 | Identification, designation, and categorization of involved uncertainties

As the specifics of the decision problem are known, it is possible to identify four uncertainty issues listed in Table 1. EDM has to cope with potential impacts in natural systems that occur in extended temporal and spatial scales (Dovers, 2005). For example, the extraction of oil (demanded by oil heating systems) may lead to natural disasters, such as the consequences from the Deepwater Horizon oil spill. Such low-probability, high-impact events are hard to assess, and thus, it is a challenge to find a reasonable integration into problem modelling. In particular, for decision makers who are not decision-making specialists (e.g., a family), such impacts may be only suspected, but not explicitly articulated. Hence, we first consider the uncertainty issue "uncertainty

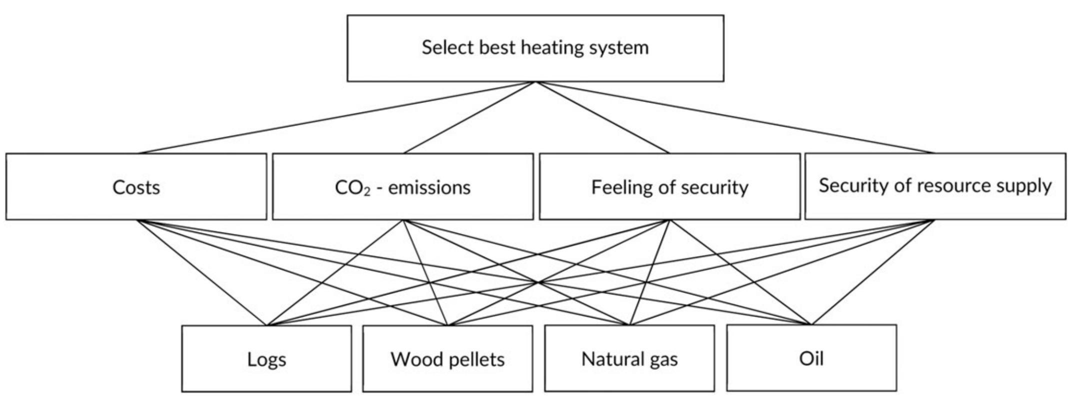

FIGURE 2 Hierarchy for a family's choice of the best heating system

TABLE 3 Characteristics of alternatives with respect to the criteria

Alternative	Criteria			
	Costs (EUR)	CO_2 emissions (kg/1 kWh useful energy)	Feeling of security	Security of resource supply
Logs	3,004	0.07	Qualitative evaluation (Table 5)	Qualitative evaluation (Table 5)
Wood pellets	3,666	0.06	Qualitative evaluation (Table 5)	Qualitative evaluation (Table 5)
Natural gas	3,772	0.26	Qualitative evaluation (Table 5)	Qualitative evaluation (Table 5)
Oil	4,547	0.39	Qualitative evaluation (Table 5)	Qualitative evaluation (Table 5)

associated with the incorporation of important, but 'unknown' factors."

This perceived inscrutability of dependencies likely leads to situations that cause missing elements in a pairwise comparison matrix. For example, the two children have to evaluate the involved alternatives under the criterion Security of resource supply. They might not be able to accurately judge, because the pairwise comparison requires knowledge (e.g., knowledge about international energy politics as a consequence of Russian's foreign affairs) that children usually do not have. So we incorporate "uncertainty associated with incomplete pairwise comparison matrices" as second uncertainty issue in the analysis.

We also consider "uncertainty associated with the aggregation mode between the different levels of the problem modelling hierarchy" as relevant, because of its long-lasting and fundamental debate (see Section 4.3.6); a direct deduction from the decision problems' characteristics stays hidden, but family has no idea of the consequences of the aggregation mode decision.

Solving "sustainability problems" in a sustainable way requires the involvement of relevant stakeholders. It is likely that this "community participation" enhances the acceptance of the decision outcome (Dovers, 2005; Harding et al., 2009). Hence, also the children are included in making the decision. Therefore, the "uncertainty associated with the combination procedure of several decision makers' judgments" is seen as important for this case. With respect to the possible classifications of uncertainty (cf. Table 2), the designated and categorized uncertainties are summarized in the following Table 4.

Apparently, within the categorization dimension, the generic location varies and predominantly embraces Model structure uncertainty reflecting that the model structure of the AHP methodology does not provide a genuine algorithmic treatment to consider a specific uncertainty derived from decision-making practice. The type of uncertainty Ambiguity and the uncertainty's nature Epistemic are chosen for each uncertainty, because due to any modeller's incomplete knowledge, it is unclear which algorithmic treatment should be considered as the genuine one. From a methodological point of view, this reflects the difficulty to choose the best procedure to incorporate a specific uncertainty into the AHP methodology. However, an argumentation for a chosen incorporation is necessary (see Sections 4.3.4 to 4.3.6).

4.3 | Quantification of involved uncertainties

4.3.1 | Implementation of three variants

Technically, the three variants considered in this case study differ in the determined preference tendencies (PTs). This is a determination of a specific relative importance ranking (Butler, Jia, & Dyer, 1997) for every qualitative evaluation (e.g., A is more preferred than B, but it is not determined how much more, then A is ranked as 1 and B as 2).

- With respect to specific stereotypes, the determination of the PTs of Variant I is shown in Table 5. For example, the father is conceived as a performance-minded self-made man representing some kind of value oriented tenor. He thinks that the criterion Costs is more important as the criterion Security of resource supply, which itself is more important as the criterion CO_2 emissions (Table 5d).
- As the alternatives Logs and Wood pellets show performance advantages under the criteria Costs and CO_2 emissions, all family members are determined to evaluate them equally and in line with the structure embedded in the data (Table 3). For example, with regard to the criterion Feeling of security, the whole family evaluates Logs as more important than Wood pellets than Natural gas than Oil (Table 5a). The determination of the PTs of Variant II is provided in Table 5.
- Maximal diverging preferences of the family members are implemented by programming that each object to be evaluated is ranked on all positions over all family members within each evaluation. This ranking is based on a random algorithm. The resulting determination of the PTs of Variant III is presented in Table 5.

TABLE 4 Designation and categorization of uncertainties according to the different steps of multicriteria decision making

	Designation of uncertainty			
	Model conceptualization (problem modelling)	Incomplete pairwise comparison matrix (weights valuation)	Aggregation mode (weights aggregation)	Group aggregation method (group decision making)
Case study context	Family suspects unknown factors	Family has insufficient knowledge to judge	Family has no idea of the consequences of the aggregation mode decision	Participation of all family members assumed
Categories				
Generic location	Context	System data	Model structure uncertainty	Model structure uncertainty
Type	Ambiguity	Ambiguity	Ambiguity	Ambiguity
Nature	Epistemic, Variability	Epistemic	Epistemic	Epistemic

TABLE 5 Preference tendency for all qualitative evaluations

(a) Preference tendency: Relative importance ranking with respect to criterion Feeling of security

	Family member	Alternatives			
		Logs	Wood pellets	Natural gas	Oil
Variant I	Father	1	2	3	4
	Mother	2	1	4	3
	Child 1	2	4	1	3
	Child 2	4	3	2	1
Variant II	Father	1	2	3	4
	Mother	1	2	3	4
	Child 1	1	2	3	4
	Child 2	1	2	3	4
Variant III	Father	4	3	1	2
	Mother	1	2	4	3
	Child 1	2	4	3	1
	Child 2	3	1	2	4

(b) Preference tendency: Relative importance ranking with respect to criterion "other"

	Family member	Alternatives			
		Logs	Wood pellets	Natural gas	Oil
Variant I	Father	1	4	3	2
	Mother	3	1	2	4
	Child 1	1	4	2	3
	Child 2	4	2	3	1
Variant II	Father	1	2	3	4
	Mother	1	2	3	4
	Child 1	1	2	3	4
	Child 2	1	2	3	4
Variant III	Father	2	1	4	3
	Mother	1	2	3	4
	Child 1	3	4	1	2
	Child 2	4	3	2	1

(c) Preference tendency: Relative importance ranking with respect to criterion Resource supply

	Family member	Alternatives			
		Logs	Wood pellets	Natural gas	Oil
Variant I	Father	1	3	4	2
	Mother	3	1	2	4
	Child 1	2	4	1	3
	Child 2	4	2	3	1
Variant II	Father	1	2	3	4
	Mother	1	2	3	4
	Child 1	1	2	3	4
	Child 2	1	2	3	4
Variant III	Father	1	3	2	4
	Mother	3	4	1	2
	Child 1	4	2	3	1
	Child 2	2	1	4	3

(d) Preference tendency: Relative importance ranking with respect to criteria

	Family member	Criteria			
		Costs	CO_2 emissions	Feeling of Security	Security of resource supply
Variant I	Father	1	3	4	2
	Mother	3	2	1	4
	Child 1	3	1	2	4
	Child 2	4	1	2	3
Variant II	Father	1	2	3	4
	Mother	1	2	3	4
	Child 1	1	2	3	4
	Child 2	1	2	3	4
Variant III	Father	1	2	3	4
	Mother	2	4	1	3
	Child 1	3	1	4	2
	Child 2	4	3	2	1

4.3.2 | Design of the USs

As posed in Section 4.2, the scope of the application is determined to the incorporation of four uncertainties (see Sections 4.3.4 to 4.3.7). The "✓" sign in Table 6 represents the inclusion of the specific uncertainty in the computing of the global priority vectors and the "✘" sign an exclusion, respectively. Coupling the seven USs with the two group aggregation methods leads to 14 different combinations. Additionally, two scenarios only including the respective versions of the original AHP are computed.

4.3.3 | Steps of simulation experiment

The sequence of the simulation experiment is shown in Figure 3 as a flow chart of the computation of two major steps: (a) The original AHP is programmed and validated against literature examples, and

TABLE 6 Overview uncertainty scenarios and original versions of analytic hierarchy process (AHP)

Uncertainty scenarios (USs) and two versions of original AHP	Uncertainties			
	Model conceptualization	Incomplete pairwise comparison matrix	Aggregation mode	Group aggregation method
Original AHP_wam	✘	✘	✘	Weighted arithmetic mean (wam)
US1_wam	✓	✘	✘	wam
US2_wam	✘	✓	✘	wam
US3_wam	✘	✘	✓	wam
US4_wam	✓	✓	✓	wam
US5_wam	✓	✓	✘	wam
US6_wam	✓	✘	✓	wam
US7_wam	✘	✓	✓	wam
Original AHP_gm	✘	✘	✘	Geometric mean (gm)
US1_gm	✓	✘	✘	gm
US2_gm	✘	✓	✘	gm
US3_gm	✘	✘	✓	gm
US4_gm	✓	✓	✓	gm
US5_gm	✓	✓	✘	gm
US6_gm	✓	✘	✓	gm
US7_gm	✘	✓	✓	gm

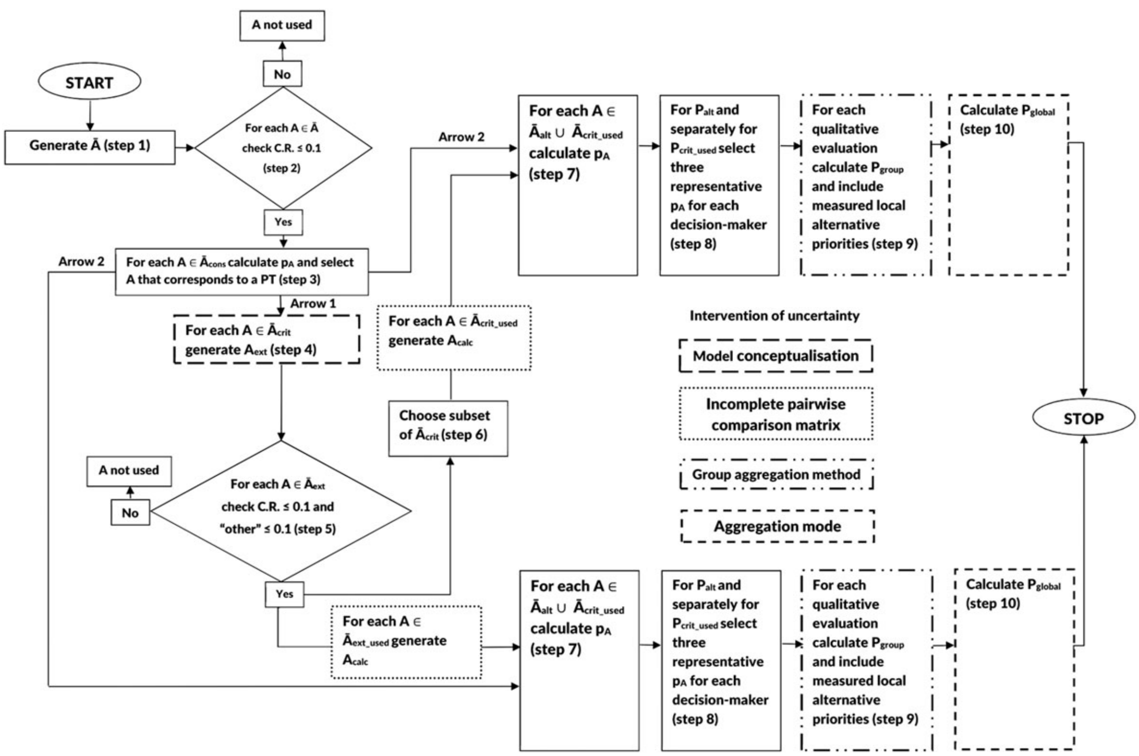

FIGURE 3 Flow chart of steps of simulation experiment

(b) the USs are implemented in this algorithm using the programming language of R (R, 2014). With respect to the computed USs, the dashed lines represent the locations where the single uncertainties intervene. The algorithmic procedure is detailed explained by the following single steps:

Step 1 Generate $\bar{A}$. Let $\mathbf{A} = (a_{ij})$ be an $n \times n$ positive reciprocal pairwise comparison matrix where $i,j \in \{1, \ldots, 4\}$. Let S: = {1/9, 1/8, 1/7, ...1, 2, ..., 8, 9} denote the Saaty (1986) scale and the set of values used for the randomly chosen input data for **A**. The diagonal elements $a_{ii} = 1$ for all i and $a_{ij} \in S$ where $p(a_{ij})$: = 1/|S| where $i < j$ and $a_{ji} = 1/a_{ij}$. $\bar{A}$: = {**A**: **A** is a positive reciprocal pairwise comparison matrix} where $|\bar{A}| = 3 * 10^6$. For conducting simulation experiments with respect to the AHP methodology, different authors used various amounts of random pairwise comparison matrices. The maximal amount of a few millions was used by Aull-Hyde, Erdogan, and Duke (2006) or Herman and Koczkodaj (1996). Based on that experience, we also consider a pool of $3 * 10^6$ random pairwise comparison matrices as sufficient.

Step 2 For each $\mathbf{A} \in \bar{A}$, check C.R. $\leq$ 0.1. Each pairwise comparison matrix **A** is then checked if it is consistent by calculating the consistency ratio (C.R.). Let C.I. be the consistency index, where C.I.: = $(\lambda_{max} - n)/(n - 1)$ and λ_{max} is the largest eigenvalue of **A**. Let R.I. be the average random index (Saaty, 1996). C.R. := C.I./R.I. and **A** is considered of acceptable consistency when C.R. $\leq$ 0.1. Let $\bar{A}_{cons}$ denote the set of all consistent pairwise comparison matrices **A**.

Step 3 For each $\mathbf{A} \in \bar{A}_{cons}$, calculate $\mathbf{p}_A$ and select **A** that corresponds to a PT. Simulating group decision processes requires some determinism; otherwise, it would become an overwhelming task. Hence, for each family member and for every qualitative evaluation, a specific PT is determined (Table 5). No numerical weights are used in this step. Technically, this determination is implemented by calculating all priority vectors $\mathbf{p}_A$ of each $\mathbf{A} \in \bar{A}_{cons}$ using the exact method (Saaty, 1995). It is assumed that all comparisons have the same order of magnitude; hence, no clustering is needed. Only those pairwise comparison matrices and their computed vector of relative importance are selected that correspond to any determined PT. Let $\bar{A}_{PT}$ denote the set of all consistent pairwise comparison matrices **A** that correspond to a PT. $\bar{A}_{crit}$ denotes the set of matrices **A** that correspond to the PTs of the criteria evaluation, and $\bar{A}_{alt}$ denotes the set of matrices **A** that correspond to alternatives' performance under a specific criterion. $\bar{A}_{crit} \cup \bar{A}_{alt} = \bar{A}_{PT}$. As the *MODEL CONCEPTUALIZATION* uncertainty is determined to intervene in the calculation of the criteria priorities (see Section 4.3.4), "Arrow 1" in Figure 3 notifies the transfer of $\bar{A}_{crit}$ to Step 4. "Arrow 2" represents the transfer of $\bar{A}_{alt}$ to Step 7.

Step 4 For each $\mathbf{A} \in \bar{A}_{crit}$ generate $\mathbf{A}_{ext}$. As indicated in Figure 3, Step 4 includes an intervention point of the *MODEL CONCEPTUALIZATION* uncertainty. Within this step, a criterion "other" is implemented (Ozdemir & Saaty, 2006), which calculates the extension $\mathbf{A}_{ext}$ of the pairwise comparison matrices $\mathbf{A} \in \bar{A}_{crit}$ (see Section 4.3.4). Let $\mathbf{A}_{ext} = (a_{ij}^{ext})$ be an $n \times n$ positive reciprocal pairwise comparison matrix, where $i, j \in \{1, \ldots, 5\}$. For $\mathbf{A}_{ext}$, we set (a_{ij}^{ext}): = (a_{ij}^{crit}) for $i,j \in \{1, \ldots, 4\}$. For the new required comparisons a_{ij}^{ext} where $i \in \{1, \ldots, 4\}$ and $j = 5$, S is used for the randomly chosen input data where $p(a_{ij}^{ext})$: = 1/|S|. The new diagonal element $a_{55} = 1$ and for the new required comparisons $a_{ji}^{ext} = 1/a_{ij}^{ext}$. Let $\bar{A}_{ext}$ denote the set of all consistent pairwise comparison matrices that refer to the criteria evaluation and that are modified with respect to the *MODEL CONCEPTUALIZATION* uncertainty.

Step 5 For each $\mathbf{A} \in \bar{A}_{ext}$, check C.R. $\leq$ 0.1 and "other" $\leq$ 0.1. Ozdemir and Saaty (2006) recommend only to make a decision when the criterion "other" does not exceed a relative importance of about 10%. It is assumed that the criterion "other" is not an "indifferent criteria," indicating that the alternatives perform differently under this criterion (Pérez, Jimeno, & Mokotoff, 2006). Also, for this qualitative evaluation, a PT for each family member is determined. In this task, it is checked if the extended pairwise comparison matrices are still consistent (C.R. $\leq$ 0.1) and if the criterion "other" does not exceed a relative importance of 10% (Ozdemir & Saaty, 2006; Saaty, 1995; see Section 4.3.4). Let $\bar{A}_{ext\_used}$ denote the set of all consistent pairwise comparison matrices that refer to the criteria evaluation, that are modified with respect to the *MODEL CONCEPTUALIZATION* uncertainty, and that satisfy C.R. $\leq$ 0.1 and "other" $\leq$ 0.1.

Step 6 Choose subset of $\bar{A}_{crit}$. Because of the intention to calculate an "overall uncertainty" measure that compares the result of the original AHP with the respective USs (see Section 4.3.8), only specific pairwise comparison matrices derived from Step 3 can be used to compute the two versions of the original AHP (Table 6). In particular, only those that refer to the subset caused by Steps 4 and 5. This subset of $\bar{A}_{crit}$ is denoted by $\bar{A}_{crit\_used}$.

Step 7 For each $\mathbf{A} \in \bar{A}_{alt} \cup \bar{A}_{crit\_used}$, calculate $\mathbf{p}_A$. The previous steps determine which pairwise comparison matrices are used in further calculations. For every pairwise comparison matrix $\mathbf{A} \in \bar{A}_{alt} \cup \bar{A}_{crit\_used}$, a priority vector $\mathbf{p}_A$ is computed using the exact method (Saaty, 1995). If the matrices are modified due to inclusion of a US that includes the *MODEL CONCEPTUALIZATION* uncertainty or the *INCOMPLETE PAIRWISE COMPARISON MATRIX* uncertainty, then another calculation of $\mathbf{p}_A$ with modified matrices is performed. Let P_{alt} denote the set of $\mathbf{p}_A$ for each $\mathbf{A} \in \bar{A}_{alt}$ and P_{crit_used} the set of $\mathbf{p}_A$ for each $\mathbf{A} \in \bar{A}_{crit\_used}$.

Step 8 For P_{alt} and separately for P_{crit_used}, select three representative $\mathbf{p}_A$ for each decision maker. This step includes the selection of three representative objects (medoids, in this case a single priority vector) of a set of preference vectors that relate to a specific PT and a specific decision maker. Let M_{DM} denote the set of three medoids representing a set of preference vectors that relate to a specific PT and a specific decision maker. As presented in Section 4.1.1, the decision problem embraces four decision makers. The selection is done by implementing a cluster algorithm (function PAM from the R package “cluster”; Rousseeuw, Struyf, & Hubert, 2014).

Step 9 For each qualitative evaluation, calculate P_{group}. P_{group} is calculated for each qualitative evaluation. P_{group} is based on all four M_{DM} and contains all possible group preference vectors derived by applying the weighted arithmetic mean on the decision makers' criteria and local alternative priorities. All decision makers have equal weights in the group decision procedure (see Section 4.3.7). From a combinatorics point of view, there are 3^4 possible combinations; hence, $|P_{group}|$ = 81. As not all evaluations are based on subjective pairwise comparisons, local alternative priorities based on absolute measurement are included here. For the alternatives' performance under the criteria Costs and CO_2 emissions, available quantified data (Table 3) were used and transformed into a vector of relative importance by converting it to relative scale measurements through normalization.

Step 10 Calculate P_{global}. This step includes the computation of the final alternative priorities by using the additive aggregation or the multiplicative aggregation mode (Saaty, 1995). With respect to the program algorithm for each original AHP and each US, in total, 531,441 global priority vectors are calculated. It is important to note that all simulation runs are initially based on $\bar{A}$ (Table 7). Let P_{global} denote the set of global priority vectors $\mathbf{p}_A$ for each original AHP and each US. Linking the USs to the program flow chart, for example, the results for US1_wam can be computed following Steps 1 to 5 and then moving to Step 7 completing after Step 10. This computation only includes the intervention of the *MODEL CONCEPTUALIZATION* uncertainty in Step 4. For comparison purposes with respect to the “overall uncertainty” measure, the respective version of the original AHP, Original AHP_wam, is computed by following Steps 1 to 10. For details concerning the implementation of the uncertainties and the calculation of the “overall uncertainty” measure, refer to Sections 4.3.4 to 4.3.8 below.

4.3.4 | Model conceptualization uncertainty

Uncertainty associated with the development of the model structure is inherently related to the formulation of a decision hierarchy (Belton & Stewart, 2002; Jakeman, Voinov, Rizzoli, & Chen, 2008). There are no rules which hierarchical representation is most suitable to a specific decision making problem. Different analysts show varying problem perceptions and thus come up with different decision models (Refsgaard, Van der Sluijs, Højberg, & Vanrolleghem, 2005). Brugha (1998, 2004) offers methodological suggestions how to elaborate structured criteria trees. Also, Wedley (1990) provides guidelines what to include in hierarchies. Saaty and Begicevic (2010) propose general lists of human values and activities to support problem structuring, that is, to ensure the inclusion of all important elements. Nevertheless, if a model is set up, questions such as “are all relevant factors considered?” or “are there relevant criteria remaining that are suspected, but cannot explicitly articulated?” may arise (Ozdemir & Saaty, 2006). If there is awareness that there are other important criteria covering some “unknown” factors, a way to integrate them into the problem formulation has to be identified. Ozdemir and Saaty (2006) propose the implementation of another criterion, called “other,” into the AHP model to check whether the best alternative is sensitive to hidden factors. The criterion “other” is introduced as additional criteria into the model and hence undergoes the common pairwise comparison process. It expresses the confidence about covering all relevant aspects regarding the decision problem. As explained in Section 4.3.3, by generating $\bar{A}_{ext\_used}$ (see Steps 4 and 5), only the set of criteria is complemented by the criterion “other.” Furthermore, the criterion “other” should not exceed a relative importance of about 10%. This leads to another important assumption in this case: A minimum of 90% (maximal 10% is allocated to the criterion “other”) of the former relative importance of the four criteria included in the problem modelling is sufficient to allow the assumption that these two matrices, the not-extended one ($\mathbf{A}$) and the extended one ($\mathbf{A}_{ext}$) and its related priority vectors, are comparable. Matrix $\mathbf{A}$ (1) and matrix $\mathbf{A}_{ext}$ (2) as well as their related priority vectors, denoted as $\mathbf{p}_A$ and $\mathbf{p}_{A_{ext}}$, provide a numerical example of this assumption taken from the simulation experiment.

TABLE 7 Overview of defined sets

Set	Step	Important characteristic	Size of A
$\bar{A}$	1	$\bar{A}$: = {**A**: **A** is a positive reciprocal pairwise comparison matrix}	4 × 4
$\bar{A}_{cons}$	2	$\bar{A}_{cons}$: = {**A**: **A** ∈ $\bar{A}$ and C.R. ≤ 0.1}	4 × 4
$\bar{A}_{crit}$	3	$\bar{A}_{crit}$: = {**A**: **A** ∈ $\bar{A}_{cons}$ and corresponds to the PTs of the criteria evaluation}	4 × 4
$\bar{A}_{alt}$	3	$\bar{A}_{alt}$: = {**A**: **A** ∈ $\bar{A}_{cons}$ and corresponds to the PTs of the alternatives' performance under a specific criterion}	4 × 4
$\bar{A}_{PT}$	3	$\bar{A}_{PT}$: = $\bar{A}_{crit} \cup \bar{A}_{alt}$	4 × 4
$\bar{A}_{ext}$	4	$\bar{A}_{ext}$: = {**A**: **A** ∈ $\bar{A}_{crit}$ and extended with respect to the *MODEL CONCEPTUALIZATION* uncertainty}	5 × 5
$\bar{A}_{ext\_used}$	5	$\bar{A}_{ext\_used}$: = {**A**: **A** ∈ $\bar{A}_{ext}$ and C.R. ≤ 0.1 and “other” ≤ 0.1}	5 × 5
$\bar{A}_{crit\_used}$	6	$\bar{A}_{crit\_used}$: = {**A**: **A** ∈ $\bar{A}_{ext\_used}$ and $\left(a_{ij}^{crit\,used}\right) := \left(a_{ij}^{ext\,used}\right)$ for $i,j \in \{1, \ldots, 4\}$}	4 × 4
P_{alt}	7	P_{alt}: = {$\mathbf{p}_A$: priority vector for **A** ∈ $\bar{A}_{alt}$}	—
P_{crit_used}	7	P_{crit_used}: = {$\mathbf{p}_A$: priority vector for **A** ∈ $\bar{A}_{crit\_used}$}	—
M_{DM}	8	M_{DM}: = {medoid: representative $\mathbf{p}_A$ for P_{alt} and P_{crit_used} for each decision maker}	—
P_{group}	9	P_{group}: = {$\mathbf{p}_A$: group preference vector}	—
P_{global}	10	P_{global}: = {$\mathbf{p}_A$: global priority vector for each original AHP and each US}	—

Note. PT: preference tendency; US: uncertainty scenario; C.R.: consistency ratio; AHP: analytic hierarchy process.

$$\mathbf{A} = \begin{pmatrix} 1 & 9 & 7 & 1 \\ 1/9 & 1 & 3 & 1/8 \\ 1/7 & 1/3 & 1 & 1/6 \\ 1 & 8 & 6 & 1 \end{pmatrix} \mathbf{p}_{\mathrm{A}} = \begin{pmatrix} 0.45 \\ 0.08 \\ 0.05 \\ 0.42 \end{pmatrix}, \quad (1)$$

$$\mathbf{A}_{\mathrm{ext}} = \begin{pmatrix} 1 & 9 & 7 & 1 & 7 \\ 1/9 & 1 & 3 & 1/8 & 2 \\ 1/7 & 1/3 & 1 & 1/6 & 2 \\ 1 & 8 & 6 & 1 & 7 \\ 1/7 & 1/2 & 1/2 & 1/7 & 1 \end{pmatrix} \mathbf{p}_{\mathrm{A_{ext}}} = \begin{pmatrix} 0.42 \\ 0.08 \\ 0.05 \\ 0.40 \\ 0.05 \end{pmatrix}. \quad (2)$$

For this case, the two rankings of the criteria are equivalent, but the implementation of the criterion “other” with its relative importance of 0.05 changed the criteria's relative importance.

4.3.5 | Incomplete pairwise comparison matrix uncertainty

Dittrich, Francis, Hatzinger, and Katzenbeisser (2012) identifies six different situations that can cause missing elements in a pairwise comparison matrix, of which one is relevant for the case study decision problem: Respondents may fail to respond, because of their insufficient knowledge to judge (see Section 4.2). Deparis, Mousseau, Öztürk, Pallier, and Huron (2012) empirically investigates the expression of incomplete preferences linked to multicriteria comparisons and reports that evaluating procedures that do not design the inclusion of incomplete preferences may lead to the expression of an indifference response instead of an incomplete expression. Incomplete pairwise comparison matrices may appear with a differing number of missing elements. Hence, to tackle one of these cases, several procedures (e.g., transitivity rules or applying consistency optimization and simulation techniques) are provided in literature (Bozóki, Fülöp, & Rónyai, 2010; Kwiesielewicz & Van Uden, 2003). The chosen method of calculating the missing data implicitly embeds a specific intention with respect to the decision makers; hence at the beginning of the recalculation, it is necessary to clarify these intentions and then to choose the most suitable method (Kwiesielewicz & Van Uden, 2003). Humans understand the meaning of words better and hence prefer to use verbal expressions. They are intuitively appealing and more common in our everyday lives than numbers (Huizingh & Vrolijk, 1997; Ishizaka & Labib, 2011a). To tackle this human characteristic, we choose the first-level transitivity rule proposed by Srdjevic, Srdjevic, and Blagojevic (2014), because it only uses values from the Saaty scale to recalculate missing elements. These values correspond to exact semantic statements, which can be used for communication and queries with the involved decision makers (Saaty, 1995).

As indicated in Figure 3, the uncertainty *INCOMPLETE PAIRWISE COMPARISON MATRIX* may intervene at two locations of the algorithm. One location is between Step 6 and Step 7, indicating the modification of a not-extended pairwise comparison matrix (**A**), and the second location is between Step 5 and Step 7, meaning a modification of an extended pairwise comparison matrix ($\mathbf{A}_{\mathrm{ext}}$). In both cases, it is assumed that the arbitrary elements a_{14} and its reciprocal a_{41} are missing, which is denoted by * (4).

Also here, it is assumed that this modification is marginal enough to allow its comparability with not modified matrices. Matrix **A** (3) and matrix $\mathbf{A}_{\mathrm{calc}}$ (5) as well as their related priority vectors, denoted as $\mathbf{p}_{\mathrm{A}}$ and $\mathbf{p}_{\mathrm{A_{calc}}}$, provide a numerical example of this implementation taken from the simulation experiment.

$$\mathbf{A} = \begin{pmatrix} 1 & 9 & 7 & 1 \\ 1/9 & 1 & 3 & 1/8 \\ 1/7 & 1/3 & 1 & 1/6 \\ 1 & 8 & 6 & 1 \end{pmatrix} \mathbf{p}_{\mathrm{A}} = \begin{pmatrix} 0.45 \\ 0.08 \\ 0.05 \\ 0.42 \end{pmatrix}, \quad (3)$$

$$\mathbf{A}^{*} = \begin{pmatrix} 1 & 9 & 7 & * \\ 1/9 & 1 & 3 & 1/8 \\ 1/7 & 1/3 & 1 & 1/6 \\ * & 8 & 6 & 1 \end{pmatrix} \mathbf{p}_{\mathrm{A}^{*}} = \text{to calculate}, \quad (4)$$

$$\mathbf{A}_{\mathrm{calc}} = \begin{pmatrix} 1 & 9 & 7 & 1 \\ 1/9 & 1 & 3 & 1/8 \\ 1/7 & 1/3 & 1 & 1/6 \\ 1/9 & 8 & 6 & 1 \end{pmatrix} \mathbf{p}_{\mathrm{A_{calc}}} = \begin{pmatrix} 0.70 \\ 0.06 \\ 0.04 \\ 0.20 \end{pmatrix}. \quad (5)$$

The ranking of the criteria is equivalent, but the implementation of a missing element and its recalculation changed the criteria's relative importance.

4.3.6 | Aggregation mode uncertainty

The original AHP relies on additive aggregation of criteria priorities and local alternative priorities to a final alternative ranking (Saaty, 1999). Criticism of this procedure has been formulated by several authors, and a multiplicative aggregation has been proposed. The referring debate is in depth summarized by Ishizaka and Labib (2011a). However, simulation experiments show differences between the usages of these two aggregation modes (Stam & Duarte Silva, 2003). To capture this fundamental debate, the implementation of the uncertainty *AGGREGATION MODE* is done by replacing the additive aggregation of the local alternative priorities by a multiplicative aggregation expressed as $P_i = \prod_j p_{ij}^{w_j}$, where P_i is the global priority of alternative i, p_{ij} is the local priority with regard to criterion j, and w_j is the weight of criterion j (Ishizaka & Nemery, 2013). This uncertainty intervenes in Step 10 of the program (Figure 3).

4.3.7 | Group aggregation method uncertainty

In the case study, the opinions of the family members have to be merged into one group decision. Given such individual judgements, several ways of aggregating them to a group decision exist. Mikhailov (2004b) presents a group fuzzy preference programming method, a Bayesian approach is developed by Altuzarra, Moreno-Jiménez, and Salvador (2007), and also procedures linking consistency considerations to a consensus view are proposed (Dong, Zhang, Hong, & Xu, 2010; Moreno-Jiménez, Aguarón, & Escobar, 2008). Additionally, Grošelj, ZadnikStirn, Ayrilmis, and Kuzman (2015) numerically compare seven simple aggregation procedures and developed measures to evaluate them. Ishizaka and Labib (2011b) summarize that there are four ways to integrate the involved decision makers' preferences into a consensus rating; two of them are mathematical procedures.

Also, Grošelj et al. identify a geometric mean on the judgements in the pairwise comparison matrices and a weighted arithmetic mean on the derived criteria and local alternative priorities as the two main mathematical aggregation algorithms. Researchers have some disagreement on the use of individual judgments in pairwise comparison matrices or for deriving criteria and local alternative priorities in a group choice (Srdjevic & Srdjevic, 2013). Criticism was formulated because the application of the geometric mean method may violate the Pareto optimality (if all group members prefer A, then a group outcome A should also be preferred; cf. Ramanathan & Ganesh, 1994) and the aggregation of criteria and local alternative priorities may violate Arrow's Impossibility Axioms (Saaty & Vargas, 2012). Forman and Peniwati (1998) argue that the perception of the group (as a synergistic unit or as a collection of individuals) determines the aggregation method to use. However, we include both options into the simulation experiment.

Step 9 of the program (Figure 3) applies both the geometric mean on the judgements in the pairwise comparison matrices and the weighted arithmetic mean on the derived family members' criteria and local alternative priorities. All family members are treated equally with respect to their point of view; hence, they have equal weights in the group decision procedure.

4.3.8 | Measurement of "overall uncertainty"

Modelling uncertainty in MCDM might be examined by using several formats representing the potential impact of uncertainty on the decision outcome (Durbach & Stewart, 2012). The computation of the different USs allows formulating a simple and intuitively understandable quantitative measure that may be interpreted as "overall uncertainty." With respect to the total runs (n = 531,441), the "overall uncertainty" measure is expressed by percentages that indicate if and how often the inclusion of a specific US changes the rank of the best alternative given by the original AHP without considering any uncertainties. For example, using the geometric mean group aggregation method, implementing US7 and computing Variant III derive an overall uncertainty measure of 51.33% (cf. Figure 4c as well). This would mean that, if the identified uncertainties included in US7 are considered, in more than half of the total runs, the best alternative given by the original AHP is replaced by other alternatives. Technically, let OAHP_wam denote the set of global priority vectors $\mathbf{p}_A$ derived by the computation of the original AHP using the weighted arithmetic mean group aggregation method (Table 6). OAHP_wam: = {$\mathbf{p}_A$_oahpwam$_i$}, where i = 1, …, n and n = 531,441. Let OAHP_gm denote the respective set using the geometric mean group aggregation method. OAHP_gm: = {$\mathbf{p}_A$_oahpgm$_i$}, where i = 1, …, n and n = 531,441. Let US_wam denote the set of global priority vectors $\mathbf{p}_A$ computed by implementing the all USs (Table 6) using the weighted arithmetic mean group aggregation method. US_wam: = {$\mathbf{p}_A$_us$_j$wam$_l$}, where j = 1, …, k and k = 7 and where l = 1, …, n and n = 531,441. Respectively, US_gm: = {$\mathbf{p}_A$_us$_j$gm$_l$}, where j = 1, …, k and k = 7 and where l = 1, …, n and n = 531,441 for using the geometric mean group aggregation method. With respect to Table 7, P_{global}: = OAHP_wam ∪ OAHP_gm ∪US_wam∪US_gm.

Further, |OAHP_wam| = |OAHP_gm| = |US_wam| = |US_gm|. The elements within each set are ordered by the pairwise comparison matrix $\mathbf{A}$ used to calculate $\mathbf{p}_A$. Hence, for all $\mathbf{p}_A$_us$_j$wam$_l$ ∈ US_wam, we use the same input data $\mathbf{A}$ as for all $\mathbf{p}_A$_oahpwam$_i$ ∈ OAHP_wam where $l = i$. Respectively, for all $\mathbf{p}_A$_us$_j$gm$_l$ ∈ US_gm, we use the same

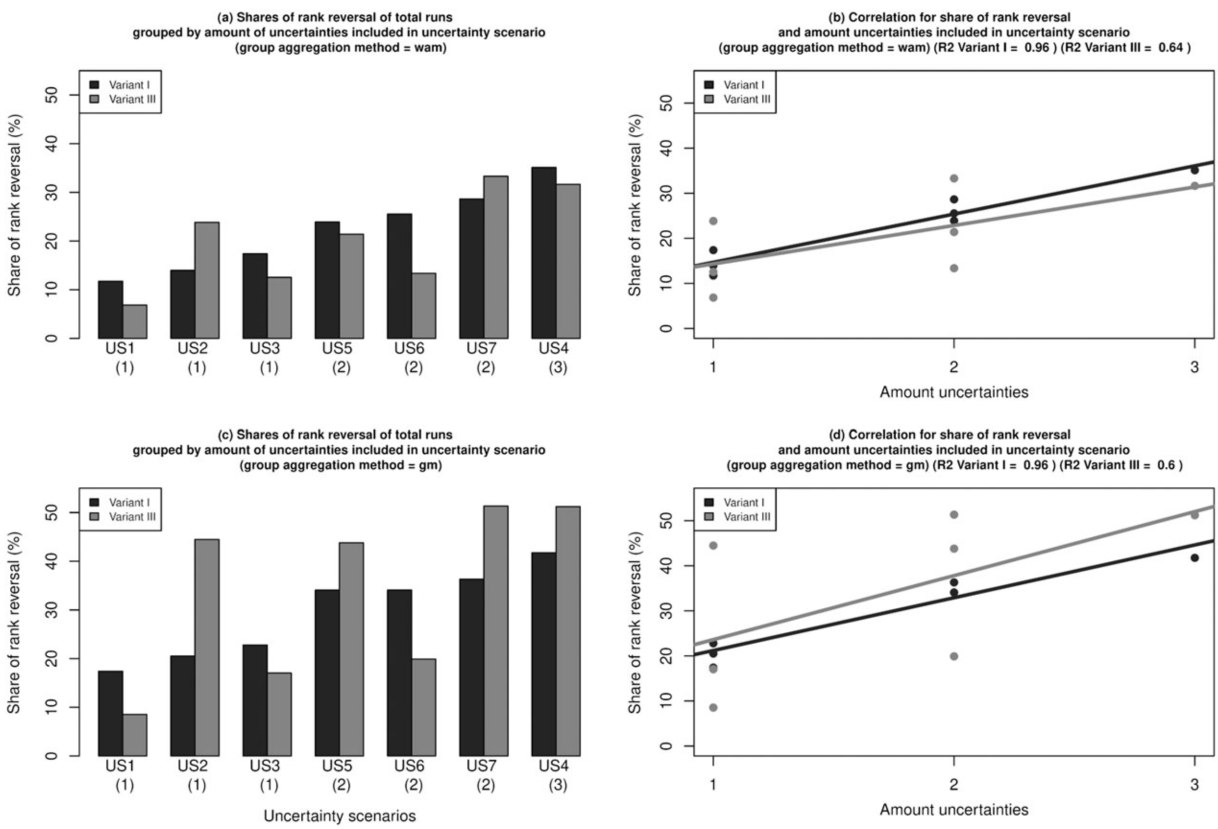

FIGURE 4 "Overall uncertainty" measure of uncertainty scenarios and correlation with amount of uncertainties for Variants I and III

input data **A** as for all $\mathbf{p}_A$_oahpgm$_i$ ∈ OAHP_gm where $l = i$. This order within each set allows to use the index for further comparisons.

To detect cases of rank reversal, all $\mathbf{p}_A$_us$_j$wam$_l$ ∈ US_wam < > $\mathbf{p}_A$_oahpwam$_i$ ∈ OAHP_wam where $l = i$. Respectively, all $\mathbf{p}_A$_us$_j$gm$_l$ ∈ US_gm < > $\mathbf{p}_A$_oahpgm$_i$ ∈ OAHP_gm where $l = i$. Then, let RR$_{wam}$: = {$\mathbf{p}_A$_us$_j$wam$_l$: $\mathbf{p}_A$_us$_j$wam$_l$ that shows a rank reversal} and RR$_{gm}$: = {$\mathbf{p}_A$_us$_j$gm$_l$: $\mathbf{p}_A$_us$_j$gm$_l$ that shows a rank reversal}. Finally, the "overall uncertainty" measure is calculated for each US j as $OUM_wam_j = \sum_{j=1}^{k} \mathbf{p}_Aus_jwam_l$ ∈ RR$_{wam}$/|OAHP_wam|, where $k = 7$ for the global priority vectors $\mathbf{p}_A$ computed by using the weighted arithmetic mean group aggregation method. Respectively, $OUM_gm_j = \sum_{j=1}^{k} \mathbf{p}_Aus_jgm_l$ ∈ RR$_{gm}$/|OAHP_gm|, where $k = 7$ for the global priority vectors $\mathbf{p}_A$ computed by using the geometric mean group aggregation method.

5 | RESULTS AND DISCUSSION

The alternatives Logs and Wood pellets show performance advantages under the criteria Costs and CO_2 emissions (Table 3). With respect to Variant II, all family members are determined to evaluate these two alternatives equally and in line with the structure embedded in the quantitative data (Table 5). For example, with regard to the criterion Feeling of security, the whole family evaluates Logs as more important than Wood pellets than Natural gas than Oil (Table 5a). Hence, the determined group preference structure magnifies the performance advantages of the alternatives Logs and Wood pellets under the criteria Costs and CO_2 emissions. The implementation of USs under Variant II does not lead to any rank reversal. From this, we can state that the impact of uncertainty decreases the more the group preference structure appears to be in line with the structure embedded in the data for the two criteria relying on quantitative data. Hence, Variant II is not being further discussed in this section.

Over both group aggregation methods and over both variants (Variants I and III), the two versions of the original AHP (Table 7) recommend either Logs or Wood pellets as best alternative with differing shares for the total runs (n = 531,441; Table 8).

Table 9 shows that the differences between the relative importance of rank 1 and rank 2 given by the original AHP of the cases undergoing a rank reversal occur only in constellations in which rank 1 and rank 2 are "very close." Over both group aggregation methods and over both variants considered, the maximal difference of relative importance of rank 1 and rank 2 that was overcome by implementing a US is approximately 0.03 for Variant III using the weighted arithmetic mean group aggregation method for the US7 (highlighted bold in Table 9). Also, the absolute maximal impact of a US over all alternatives in that cases a rank reversal occurs is very small. Using the geometric mean group aggregation method for the US5 for Variant I results in approximately 0.03 (highlighted bold in Table 10).

Over all Variants and over both group aggregation methods, Figure 4b,d shows that the more uncertainties involved in a US, the higher the "overall uncertainty" measure, which itself differs in the level of positive linear correlation. Apparently, over both group aggregation methods, the R^2 of Variant III is smaller than the R^2 of Variant I. For example, the "overall uncertainty" measure OUM_wam$_1$ using the weighted arithmetic mean group aggregation method for either Variant I or III is presented with US1 in Figure 4a. Additionally, Figure 4 a,c shows that the geometric mean group aggregation method principally causes larger shares of rank reversal; it leads in every single US over both variants to a larger "overall uncertainty" measure. According to our interpretation, this is due to fact that the geometric mean method relies directly on the entries in the pairwise comparison matrix; hence, any modification is reflected in the computed output at the local priority level. The weighted arithmetic mean group aggregation method uses the derived local priority vectors, indicating the exact method as intermediate treatment (and knowing that not perfectly consistent pairwise comparison matrices are used) of the information "blurs" (averaging of priority vectors obtained by raising pairwise comparison matrix to powers one by one) the modification

TABLE 8 Shares of best alternatives of total runs given by the original analytic hierarchy process

	Group aggregation method			
	Weighted arithmetic mean (wam)		Geometric mean (gm)	
Alternative	Variant I	Variant III	Variant I	Variant III
Logs	0.42	0.44	0.67	0.56
Wood pellets	0.58	0.56	0.33	0.44
Natural gas	0.00	0.00	0.00	0.00
Oil	0.00	0.00	0.00	0.00

TABLE 9 Descriptive statistics of absolute difference of relative importance of Ranks 1 and 2 of the results derived from the original analytic hierarchy process associated with a case of rank reversal

Uncertainty scenarios (USs)	Group aggregation method											
	Weighted arithmetic mean (wam)						Geometric mean (gm)					
	Mean		*SD*		Max		Mean		*SD*		Max	
	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III
US1	0.00341	0.00221	0.00252	0.00177	0.01427	0.01167	0.00375	0.00211	0.00266	0.00171	0.01429	0.01150
US2	0.00379	0.00660	0.00272	0.00489	0.01557	0.02890	0.00419	0.00765	0.00288	0.00504	0.01512	0.02884
US3	0.00393	0.00275	0.00236	0.00167	0.01072	0.00842	0.00413	0.00274	0.00250	0.00163	0.01101	0.00761
US4	0.00850	0.00771	0.00541	0.00523	**0.02693**	0.02930	0.00861	0.00883	0.00589	0.00576	**0.02750**	0.02935
US5	0.00578	0.00589	0.00380	0.00429	0.01994	0.02550	0.00666	0.00754	0.00438	0.00495	0.02163	0.02689
US6	0.00620	0.00377	0.00406	0.00277	0.02146	0.01620	0.00666	0.00382	0.00437	0.00269	0.02208	0.01637
US7	0.00688	0.00816	0.00445	0.00559	0.02188	**0.03117**	0.00714	0.00883	0.00468	0.00575	0.02214	**0.03097**

TABLE 10 Descriptive statistics of absolute maximal impact of uncertainty scenarios related to the results derived from the original AHP associated with a case of rank reversal over all alternatives

Uncertainty scenarios (USs)	Group aggregation method											
	Weighted arithmetic mean (wam)						Geometric mean (gm)					
	Mean		*SD*		Max		Mean		*SD*		Max	
	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III	Variant I	Variant III
US1	0.00617	0.00371	0.00467	0.00276	0.02145	0.01439	0.00731	0.00446	0.00489	0.00307	0.02455	0.01418
US2	0.00314	0.00489	0.00232	0.00331	0.01145	0.01740	0.00457	0.00607	0.00351	0.00405	0.01509	0.02117
US3	0.00913	0.00780	0.00438	0.00443	0.01895	0.02093	0.00922	0.00776	0.00426	0.00428	0.01760	0.01881
US4	0.00768	0.00822	0.00528	0.00574	**0.02385**	0.02714	0.00841	0.00776	0.00567	0.00370	0.02885	0.01996
US5	0.00690	0.00491	0.00533	0.00338	0.02362	0.01692	0.01050	0.00634	0.00646	0.00444	**0.03012**	0.02100
US6	0.00732	0.00554	0.00494	0.00388	0.02383	0.02045	0.00694	0.00512	0.00471	0.00369	0.02271	0.01995
US7	0.00836	0.00916	0.00599	0.00675	0.02342	**0.02850**	0.00765	0.00848	0.00504	0.00515	0.02114	**0.02439**

examined in the pairwise comparison matrix (Saaty, 1995). However, this assumption has to be tested numerically. Nevertheless, attention should be given to the kind of group aggregation method is used (Forman & Peniwati, 1998).

As shown in Figure 4a,c, similar shares of rank reversal occur within a single variant for USs including differing number of uncertainties and varying uncertainties. For example, for Variant I, computing US3 using the weighted arithmetic mean group aggregation method and US1 using the geometric mean group aggregation method leads to comparable results. For Variant III, computing US5 using the weighted arithmetic mean group aggregation method and US6 using the geometric mean group aggregation method results in comparable shares of rank reversal.

With respect to the "overall uncertainty" measure, the shares of rank reversal vary over the computed USs. The maximal share of rank reversal (35.11% of total runs n = 531,441) using the weighted arithmetic mean group aggregation method occurs in Variant I implementing US4 (Figure 4a). Respectively, using the geometric mean group aggregation method, US7 computing Variant III gives the maximum of 51.33% (Figure 4c). Interpreting this from a normative point of view, it would be alarming. But, taking a look at the sizes of the differences of relative importance of Ranks 1 and 2 that was overcome (Table 9), it becomes from a practitioner's point of view relativized.

As described in Section 4.3.3, the algorithm for the quantification of the uncertainty issues related to the case study is based on several assumptions (e.g., usage of a specific set of input data [Step 1] or equal weights for single each family member [Step 9]). Each of these assumptions could be implemented differently (e.g., structures of randomly derived matrices may differ from structures of real world matrices; Bozóki, Dezső, Poesz, & Temesi, 2013; Gass & Standard, 2002), or there could be reasons to give different weights to group members (Ishizaka & Nemery, 2013; Saaty & Peniwati, 2013). As the function PAM from the R-package "cluster" is a more robust version of K-means (Rousseeuw et al., 2014), we believe that three medoids for representing a sample of vectors within Step 8 of the simulation experiment are feasible for the purpose of our study. With respect to the overview of uncertainty issues associated with the AHP (Table 1), another meta-choice was made. The overview does not claim completeness; hence, further developments could enlarge the scope of uncertainties considering aspects prior the actual application of the AHP as well. Additional uncertainty issues could be included. For example, relating to the gathering of data and information (Beynon, 2002b; Beynon, Curry, & Morgan, 2000), concerned about scenario planning (Durbach & Stewart, 2003; Stewart, French, & Rios, 2013) or uncertainty issues associated with problem structuring (Marttunen, Lienert, & Belton, 2017). Furthermore, they could be related to widespread software implementations of the AHP, such as "Expert Choice" (Ishizaka & Labib, 2009) or a subtler differentiation within a single uncertainty issue could be elaborated. However, our meta-choices and assumptions, i.e. which uncertainties should be included and in which way, narrowed and pre-determined to some extend the solution space of the simulation experiment.

6 | CONCLUSIONS

We showed in our review that the fundamental characteristics of sustainability problems in EDM claim the application of methodological extensions of the original AHP. With respect to the case study, we can further conclude:

Human intervention in natural systems causes potential and uncertain impacts that occur at different temporal and spatial scales and need to be considered in EDM. Such important but unknown factors make it necessary to extend the modelled decision problem by a measure that expresses the confidence about covering all relevant aspects of the decision problem, for example, by the criterion "other" (Ozdemir & Saaty, 2006). However, in a group decision-making context, it will be important to discuss the implications of such an extension, as there is a need to develop a common understanding among the participants, which requires an additional harmonization process. Due to the inherent complexity in EDM, insufficient knowledge to judge or make a choice among options is a common challenge for lay people in decision making. Especially in the context of estimating preference values for the pairwise comparison matrix, software products relying on the original AHP should be extended by a procedure to evaluate the effects of such missing information. A procedure is, for example, provided by the first-level transitivity rule for one missing element (Srdjevic et al., 2014). Participatory approaches in EDM enhance the acceptance level of the final decision outcome. Hence, the increasing need for community participation asks for methods to merge individuals' judgements to a group decision in order to increase the final acceptance. Ossadnik, Schinke, and Kaspar (2016) provide a comprehensive comparison of aggregation approaches that allow selecting an appropriate technique. However, the choice of a single aggregation method for a specific decision-making problem is a subject of debate.

Evidently and as indicated in the discussion, the application of the proposed comprehensive uncertainty analysis involves some subjective and behavioural impact of the applicant as it has to be chosen which methodological extension of the AHP should be applied to cope with an identified uncertainty. We provided arguments for each of our choices and computed three variants to ensure results with implications for decision-making practice.

The numerical implementation of these extensions indicates that it is of particular interest for decision makers to consider such aspects in EDM. The results of the simulation experiment show that considering uncertainty issues may lead to a different choice of the best alternative. The maximal share of rank reversal was 51.33%, and the maximal difference of relative importance of Ranks 1 and 2—in implementing a US—was close to 0.03.

The interpretation of the results depends on the perception of the decision problem. The consideration of uncertainty may lead to a rank reversal in comparison with an analysis neglecting uncertainty issues. Hence, the decision outcome is basically shaped by meta-decisions and behavioural aspects of the decision makers. Accordingly and from a theoretical normative point of view, the effects of considering uncertainty issues in the AHP methodology cannot satisfy the ideal of a rational decision analysis. From a descriptive point of view, considering the practice of decision makers, in our case study, the numerical impacts of the considered uncertainties stay within reasonable limits, meaning that the maximal numerical impact of uncertainty stays on the hundredths decimal place.

In those cases where the best two options are very similar according to their performance, uncertainty might impact the final alternative ranking in a way that a rank reversal occurs. For both perspectives, it is obvious that the interpretation of the uncertainty's impact on the final alternative ranking can only be examined related to a specific decision problem.

We believe that our research can contribute to the ongoing validation debate of the AHP. Validating the AHP requires philosophical clarifications and is highly controversial (Von Solms, 2011; Whitaker, 2007). Ishizaka, Balkenborg, and Kaplan (2011) summarizes validation techniques and differentiates three groups of it. Our approach is in line with the theoretical validation group but based on claims derived from decision-making practice in the context of EDM. It is important to stress the point that we do not intend to question the general validity of the AHP with our approach. However, the relevance for decision-making practice is given if the results of the presented case study are interpreted as an extended sensitivity analysis in terms of "what happens if uncertainty associated with the original AHP is considered?"

The scope of our analysis allows drawing the conclusion that considering uncertainty in EDM practice requires generally knowledge about the potential impact of uncertainties on the final outcome, meaning that the application of the comprehensive uncertainty analysis should constitute the basis of further action. Without this knowledge, there is a high chance that decision makers put more attention to specific uncertainty aspects, which might have at the end no effect on the final decision at all. With respect to our case study, the following issues should be addressed in EDM practice:

Nearly equal shares of rank reversal for different USs with differing number of uncertainties and varying uncertainties within a single variant were observed. Our results indicate that different uncertainties involved may lead to comparable shares of rank reversals. Depending on the decision problem and from a practitioner's point of view, it is not obvious to which aspect of uncertainty should be given more attention within the decision making process. For decision analysts in EDM, this implies that under limited resources (e.g., time, budget, and staff), it may be necessary to negotiate with the participants which uncertainties should/can be addressed by which methodological extension.

Congruency of group preference structure and embedded structure of used data. The simulation experiment creates knowledge about the impact of uncertainty related to how the group preference structure appears to be in line with the embedded structure of the used data for the two criteria relying on quantitative data. This advises to start the process of incorporating uncertainties with basically clarifying the relation of the group preference structure and the used quantitative data as this may mitigate the uncertainties' impact. This finally may save resources by tackling the incorporation of uncertainties in the right place.

The geometric mean group aggregation method principally causes larger shares of rank reversal as the weighted arithmetic mean group aggregation method. Based on our results, we cannot give a recommendation which group aggregation method should be applied in practice. Further numerical simulations would have to be examined.

The derived results are valid for all decision problems including four alternatives and four criteria if these cases have identical elements of quantitative data, group characteristics, such as size, and relative importance of the members and of the expressed preferences of the group members. Decision problems embracing other structures and uncertainties may face different uncertainties' impact. The application of the comprehensive uncertainty analysis on the presented case study serves as an initial investigation that could inform further research. In particular

1. As the maximal impact of a US is intuitively very small, the simulation experiment raises questions if the combination of uncertainties and the related methodological extensions may cancel out their (single) impact on the final alternative ranking. Which combination should therefore be considered in relation to the EDM problem?
2. Which methodological extension should be chosen by decision analysts if multiple ones were developed and if still some disagreement in the scientific community exists?
3. Further research should also answer behavioural aspects, such as how decision-making practice deals with uncertainty issues

associated with AHP. Is there awareness about the implications of uncertainty in EDM and how to foster this awareness among decision makers, facilitators, stakeholders, and EDM analysts?

This discussion may further stimulate research on the application of the AHP in EDM to ensure that decision analysis is based on a comprehensive uncertainty analysis.

ACKNOWLEDGEMENTS

This work was supported by the University of Natural Resources and Life Sciences, Vienna (young scientist research grant, 2015) and by BOKU Vienna Open Access Publishing Fund. We also appreciate the valuable contributions of the anonymous reviewers that helped us to improve the manuscript substantially.

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REFERENCES

Altuzarra, A., Moreno-Jiménez, J. M., & Salvador, M. (2007). A Bayesian priorization procedure for AHP-group decision making. *European Journal of Operational Research*, *182*(1), 367–382.

Ascough Ii, J., Maier, H. R., Ravalico, J. K., & Strudley, M. (2008). Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecological Modelling*, *219*(3), 383–399.

Aull-Hyde, R., Erdogan, S., & Duke, J. M. (2006). An experiment on the consistency of aggregated comparison matrices in AHP. *European Journal of Operational Research*, *171*(1), 290–295.

Bammer, G., & Smithson, M. (2008). *Uncertainty and risk: Multidisciplinary perspectives*. London: Earthscan.

Bana e Costa, C. A., & Vansnick, J.-C. (2008). A critical analysis of the eigenvalue method used to derive priorities in AHP. *European Journal of Operational Research*, *187*(3), 1422–1428.

Barzilai, J. (2001). Notes on the analytic hierarchy process. Paper presented at the NSF Design and Manufacturing Research Conference, Tampa, Florida.

Barzilai, J. (2006). On the mathematical modelling of measurement. Retrieved from: http://arxiv.org/ftp/math/papers/0609/0609555.pdf, 10.08.2016

Barzilai, J., & Golany, B. (1994). AHP rank reversal, normalization and aggregation rules. *Infor*, *32*(2).

Belton, V., & Gear, A. (1985). The legitimacy of rank reversal—A comment. *Omega*, *13*, 143–144.

Belton, V., & Gear, T. (1983). On a short-coming of Saaty's method of analytic hierarchies. *Omega*, *11*(3), 228–230.

Belton, V., & Stewart, T. J. (2002). *Multiple criteria decision analysis: An integrated approach*. Boston: Kluwer Academic Publishers.

Bernasconi, M., Choirat, C., & Seri, R. (2010). The analytic hierarchy process and the theory of measurement. *Management Science*, *56*, 699–711.

Bernasconi, M., Choirat, C., & Seri, R. (2011). A re-examination of the algebraic properties of the AHP as a ratio-scaling technique. *Journal of Mathematical Psychology*, *55*(2), 152–165.

Beynon, M. (2002a). An analysis of distributions of priority values from alternative comparison scales within AHP. *European Journal of Operational Research*, *140*(1), 104–117.

Beynon, M. (2002b). DS/AHP method: A mathematical analysis, including an understanding of uncertainty. *European Journal of Operational Research*, *140*(1), 148–164.

Beynon, M., Curry, B., & Morgan, P. (2000). The Dempster–Shafer theory of evidence: An alternative approach to multicriteria decision modelling. *Omega*, *28*(1), 37–50.

Bozóki, S., Dezső, L., Poesz, A., & Temesi, J. (2013). Analysis of pairwise comparison matrices: An empirical research. *Annals of Operations Research*, *211*(1), 511–528.

Bozóki, S., Fülöp, J., & Rónyai, L. (2010). On optimal completion of incomplete pairwise comparison matrices. *Mathematical and Computer Modelling*, *52*(1–2), 318–333.

Brugha, C. (1998). Structuring and weighting criteria in multi criteria decision making (MCDM). Paper presented at the Trends in Multicriteria Decision Making: Proceedings of the 13th International Conference on Multiple Criteria Decision Making.

Brugha, C. M. (2004). Structure of multi-criteria decision-making. *The Journal of the Operational Research Society*, *55*(11), 1156–1168.

Bunge, M. A. (1967). *Scientific research: The search for system*. Heidelberg: Springer-Verlag.

Butler, J., Jia, J., & Dyer, J. (1997). Simulation techniques for the sensitivity analysis of multi-criteria decision models. *European Journal of Operational Research*, *103*(3), 531–546.

Cao, D., Leung, L. C., & Law, J. S. (2008). Modifying inconsistent comparison matrix in analytic hierarchy process: A heuristic approach. *Decision Support Systems*, *44*(4), 944–953.

Carmone, F. J. Jr., Kara, A., & Zanakis, S. H. (1997). A Monte Carlo investigation of incomplete pairwise comparison matrices in AHP. *European Journal of Operational Research*, *102*(3), 538–553.

Cerveny, M., & Sturm, T. (2012). Lebenszykluskosten neuer Heizsystemen für alte Einfamilienhäuser - Vergleich der Lebenszykluskosten von Heizöl-, Erdgas-, Pellet- und Scheitholzheizungen für Einfamilienhäuser in drei (+ neun) Szenarien: ÖGUT - Österreichische Gesellschaft für Umwelt und Technik.

Chen, H., & Kocaoglu, D. F. (2008). A sensitivity analysis algorithm for hierarchical decision models. *European Journal of Operational Research*, *185*(1), 266–288.

Choo, E. U., Schoner, B., & Wedley, W. C. (1999). Interpretation of criteria weights in multicriteria decision making. *Computers & Industrial Engineering*, *37*(3), 527–541.

Choo, E. U., & Wedley, W. C. (2004). A common framework for deriving preference values from pairwise comparison matrices. *Computers & Operations Research*, *31*(6), 893–908.

Choo, E. U., & Wedley, W. C. (2010). Estimating ratio scale values when units are unspecified. *Computers & Industrial Engineering*, *59*(2), 200–208.

Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators*, *46*, 138–148.

Dadkhah, K. M., & Zahedi, F. (1993). A mathematical treatment of inconsistency in the analytic hierarchy process. *Mathematical and Computer Modelling*, *17*(4–5), 111–122.

Deng, H. (1999). Multicriteria analysis with fuzzy pairwise comparison. *International Journal of Approximate Reasoning*, *21*(3), 215–231.

Deparis, S., Mousseau, V., Öztürk, M., Pallier, C., & Huron, C. (2012). When conflict induces the expression of incomplete preferences. *European Journal of Operational Research*, *221*(3), 593–602.

Dietz, T. (2003). What is a good decision? Criteria for environmental decision making. *Human Ecology Review*, *10*(1).

Dittrich, R., Francis, B., Hatzinger, R., & Katzenbeisser, W. (2012). Missing observations in paired comparison data. *Statistical Modelling*, *12*(2), 117–143.

Dodd, F. J., Donegan, H. A., & McMaster, T. B. M. (1993). A statistical approach to consistency in AHP. *Mathematical and Computer Modelling*, *18*(6), 19–22.

Donegan, H. A., & Dodd, F. J. (1991). A note on Saaty's random indexes. *Mathematical and Computer Modelling*, *15*(10), 135–137.

Dong, Y., Hong, W.-C., Xu, Y., & Yu, S. (2013). Numerical scales generated individually for analytic hierarchy process. *European Journal of Operational Research*, *229*(3), 654–662.

Dong, Y., Xu, Y., Li, H., & Dai, M. (2008). A comparative study of the numerical scales and the prioritization methods in AHP. *European Journal of Operational Research*, *186*(1), 229–242.

Dong, Y., Zhang, G., Hong, W.-C., & Xu, Y. (2010). Consensus models for AHP group decision making under row geometric mean prioritization method. *Decision Support Systems*, *49*(3), 281–289.

Dovers, S. (2005). *Environment and sustainability policy: Creation, implementation, evaluation*. Annandale: Federation Press.

Durbach, I., & Stewart, T. J. (2003). Integrating scenario planning and goal programming. *Journal of Multi-Criteria Decision Analysis*, *12*(4–5), 261–271.

Durbach, I. N., & Stewart, T. J. (2012). Modeling uncertainty in multi-criteria decision analysis. *European Journal of Operational Research*, *223*(1), 1–14.

Dyer, J. S. (1990). Remarks on the analytic hierarchy process. *Management Science*, *36*(3), 249–258.

E-Control. (2004). Wie hoch ist mein durchschnittlicher Gasverbrauch? Retrieved from: http://www.e-control.at/portal/page/portal/medienbibliothek/gas/dokumente/pdfs/durchsch-gasverbrauch.pdf, 13.01.2015

Federal Environment Agency. (2001). Sechster Umweltkontrollbericht: Federal Environment Agency - Austria.

Fedrizzi, M., & Giove, S. (2007). Incomplete pairwise comparison and consistency optimization. *European Journal of Operational Research*, *183*(1), 303–313.

Ferretti, V., & Montibeller, G. (2016). Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems. *Decision Support Systems*, *84*, 41–52.

Finan, J. S., & Hurley, W. J. (1999). Transitive calibration of the AHP verbal scale. *European Journal of Operational Research*, *112*(2), 367–372.

Finan, J. S., & Hurley, W. J. (2002). The analytic hierarchy process: Can wash criteria be ignored? *Computers & Operations Research*, *29*(8), 1025–1030.

Forman, E., & Peniwati, K. (1998). Aggregating individual judgments and priorities with the analytic hierarchy process. *European Journal of Operational Research*, *108*(1), 165–169.

Gass, S. I., & Standard, S. M. (2002). Characteristics of positive reciprocal matrices in the analytic hierarchy process. *The Journal of the Operational Research Society*, *53*(12), 1385–1389.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., & Ohlson, D. (2012). *Structured decision making: A practical guide to environmental management choices*. Chichester: Wiley.

Grošelj, P., & Stirn, L. Z. (2012). Acceptable consistency of aggregated comparison matrices in analytic hierarchy process. *European Journal of Operational Research*, *223*(2), 417–420.

Grošelj, P., ZadnikStirn, L., Ayrilmis, N., & Kuzman, M. K. (2015). Comparison of some aggregation techniques using group analytic hierarchy process. *Expert Systems with Applications*, *42*(4), 2198–2204.

Hämäläinen, R. P. (2015). Behavioural issues in environmental modelling—The missing perspective. *Environmental Modelling & Software*, *73*, 244–253.

Harding, R., Hendriks, C. M., & Faruqi, M. (2009). *Environmental decision-making: Exploring complexity and context*. Sydney: Federation Press.

Harker, P. T. (1987a). Alternative modes of questioning in the analytic hierarchy process. *Mathematical Modelling*, *9*(3–5), 353–360.

Harker, P. T. (1987b). Incomplete pairwise comparisons in the analytic hierarchy process. *Mathematical Modelling*, *9*(11), 837–848.

Harker, P. T., & Vargas, L. G. (1990). Reply to "Remarks on the analytic hierarchy process" by J. S. Dyer. *Management Science*, *36*(3), 269–273.

Herman, M. W., & Koczkodaj, W. W. (1996). A Monte Carlo study of pairwise comparison. *Information Processing Letters*, *57*(1), 25–29.

Hofmann, K. P. (Ed.) (2007). *Psychology of decision making in economics, business and finance*. New York: Nova Science Publishers.

Holder, R. D. (1990). Some comments on the analytic hierarchy process. *The Journal of Operational Research Society*, *41*(11), 1073–1076.

Hua, Z., Gong, B., & Xu, X. (2008). A DS–AHP approach for multi-attribute decision making problem with incomplete information. *Expert Systems with Applications*, *34*(3), 2221–2227.

Huber, H., Schöfmann, P., & Zottl, A. (2014).Wärme! pumpen - zur energieeffizienten Wärmeversorgung - Technologieleitfaden Wärmepumpen. Retrieved from: http://www.wien.gv.at/stadtentwicklung/energieplanung/pdf/waermepumpenleitfaden.pdf, 05.08.2016: Magistrat der Stadt Wien - Abteilung 20 - Energieplanung.

Huizingh, E. K. R. E., & Vrolijk, H. C. J. (1997). A comparison of verbal and numerical judgments in the analytic hierarchy process. *Organizational Behavior and Human Decision Processes*, *70*(3), 237–247.

Hung, M.-L., Ma, H.-W., & Yang, W.-F. (2009). Uncertainty analysis of the analytic hierarchy process methodology. *Journal of Environment Engineering and Management*, *19*(3), 145–154.

Huo, L.-A., Lan, J., & Wang, Z. (2011). New parametric prioritization methods for an analytical hierarchy process based on a pairwise comparison matrix. *Mathematical and Computer Modelling*, *54*(11–12), 2736–2749.

Ishizaka, A., Balkenborg, D., & Kaplan, T. (2011). Does AHP help us make a choice? An experimental evaluation. *Journal of the Operational Research Society*, *62*(10), 1801–1812.

Ishizaka, A., & Labib, A. (2009). Analytic hierarchy process and expert choice: Benefits and limitations. *OR Insight*, *22*(4), 201–220.

Ishizaka, A., & Labib, A. (2011a). Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications*, *38*(11), 14336–14345.

Ishizaka, A., & Labib, A. (2011b). Selection of new production facilities with the group analytic hierarchy process ordering method. *Expert Systems with Applications*, *38*(6), 7317–7325.

Ishizaka, A., & Lusti, M. (2004). An expert module to improve the consistency of AHP matrices. *International Transactions in Operational Research*, *11*, 97–105.

Ishizaka, A., & Lusti, M. (2006). How to derive priorities in AHP: A comparative study. *Central European Journal of Operations Research*, *14*(4), 387–400.

Ishizaka, A., & Nemery, P. (2013). *Multi-criteria decision analysis: Methods and software*. Chichester: Wiley.

Jakeman, A. J., Voinov, A. A., Rizzoli, A. E., & Chen, S. H. (Eds.) (2008). *Environmental modelling, software and decision support: State of the art and new perspective*. Amsterdam: Elsevier Science.

Johnson, C. R., Beine, W. B., & Wang, T. J. (1979). Right-left asymmetry in an eigenvector ranking procedure. *Journal of Mathematical Psychology*, *19*(1), 61–64.

Karapetrovic, S., & Rosenbloom, E. S. (1999). A quality control approach to consistency paradoxes in AHP. *European Journal of Operational Research*, *119*(3), 704–718.

Kiker, G. A., Bridges, T. S., Varghese, A., Seager, T. P., & Linkov, I. (2005). Application of multicriteria decision analysis in environmental decision making. *Integrated Environmental Assessment and Management*, *1*(2), 95–108.

Klir, G. J., & Yuan, B. (1995). *Fuzzy sets and fuzzy logic—Theory and applications*. Upper Saddle River: Prentice Hall PTR.

Kwiesielewicz, M., & Van Uden, E. (2003). Ranking decision variants by subjective paired comparisons in cases with incomplete data, Proceedings of the 2003 International Conference on Computational Science and Its Applications: Part III (pp. 208–215). Montreal, Canada: Springer-Verlag.

Kwiesielewicz, M., & van Uden, E. (2004). Inconsistent and contradictory judgements in pairwise comparison method in the AHP. *Computers & Operations Research*, *31*(5), 713–719.

Lamata, M. T., & Alonso, J. A. (2006). Consistency in the analytic hierarchy process: A new approach. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, *14*(04), 445–459.

Leskinen, P. (2001). Measurement scales and interval judgements in the AHP. Paper presented at the ISAHP, Berne, Switzerland.

Leung, L. C., & Cao, D. (2000). On consistency and ranking of alternatives in fuzzy AHP. *European Journal of Operational Research*, *124*(1), 102–113.

Levary, R. R., & Wan, K. (1998). A simulation approach for handling uncertainty in the analytic hierarchy process. *European Journal of Operational Research*, *106*(1), 116–122.

Liang, L., Wang, G., Hua, Z., & Zhang, B. (2008). Mapping verbal responses to numerical scales in the analytic hierarchy process. *Socio-Economic Planning Sciences*, *42*(1), 46–55.

Maier, H. R., Ascough, J. C., Wattenbach, M., Renschler, C. S., & Labiosa, W. B. (2008). Uncertainty in environmental decision making: Issues, challenges and future directions. In A. J. Jakeman, A. A. Voinov, A. E. Rizzoli, & S. H. Chen (Eds.), *Environmental modelling, software and decision support: State of the art and new perspective*. Amsterdam: Elsevier Science.

Maleki, H., & Zahir, S. (2013). A comprehensive literature review of the rank reversal phenomenon in the analytic hierarchy process. *Journal of Multi-Criteria Decision Analysis*, *20*(3–4), 141–155.

Marttunen, M., Lienert, J., & Belton, V. (2017). Structuring problems for multi-criteria decision analysis in practice: A literature review of method combinations. *European Journal of Operational Research*, *263*(1), 1–17.

May, J. H., Shang, J., Tjader, Y. C., & Vargas, L. G. (2013). A new methodology for sensitivity and stability analysis of analytic network models. *European Journal of Operational Research*, *224*(1), 180–188.

Mikhailov, L. (2004a). A fuzzy approach to deriving priorities from interval pairwise comparison judgements. *European Journal of Operational Research*, *159*(3), 687–704.

Mikhailov, L. (2004b). Group prioritization in the AHP by fuzzy preference programming method. *Computers & Operations Research*, *31*(2), 293–301.

Millet, I., & Saaty, T. L. (2000). On the relativity of relative measures—Accommodating both rank preservation and rank reversals in the AHP. *European Journal of Operational Research*, *121*(1), 205–212.

Montibeller, G., & von Winterfeldt, D. (2015). Cognitive and motivational biases in decision and risk analysis. *Risk Analysis*, *35*(7), 1230–1251.

Moreno-Jiménez, J. M., Aguarón, J., & Escobar, M. T. (2008). The core of consistency in AHP-group decision making. *Group Decision and Negotiation*, *17*(3), 249–265.

Moreno-Jimenez, J. M., & Vargas, L. G. (1993). A probabilistic study of preference structures in the analytic hierarchy process with interval judgments. *Mathematical and Computer Modelling*, *17*(4–5), 73–81.

Norton, J. P., Brown, J. D., & Mysiak, J. (2006). To what extent, and how, might uncertainty be defined? Comments engendered by "Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support": Walker et al., Integrated Assessment 4: 1, 2003. *Integrated Assessment Journal*, *6*(1), 83–88.

Ossadnik, W., Schinke, S., & Kaspar, R. H. (2016). Group aggregation techniques for analytic hierarchy process and analytic network process: A comparative analysis. *Group Decision and Negotiation*, *25*, 421–457.

Ozdemir, M. S., & Saaty, T. L. (2006). The unknown in decision making: What to do about it. *European Journal of Operational Research*, *174*(1), 349–359.

Paulson, D., & Zahir, S. (1995). Consequences of uncertainty in the analytic hierarchy process: A simulation approach. *European Journal of Operational Research*, *87*(1), 45–56.

Pérez, J., Jimeno, J., & Mokotoff, E. (2006). Another potential shortcoming of AHP. *TOP*, *14*(1), 99–111.

Pöyhönen, M. A., Hämäläinen, R. P., & Salo, A. A. (1997). An experiment on the numerical modelling of verbal ratio statements. *Journal of Multi-Criteria Decision Analysis*, *6*(1), 1–10.

R (2014). *R: A language and environment for statistical computing and graphics*. Vienna, Austria: R Foundation for Statistical Computing.

Ramanathan, R., & Ganesh, L. S. (1994). Group preference aggregation methods employed in AHP: An evaluation and an intrinsic process for deriving members' weightages. *European Journal of Operational Research*, *79*(2), 249–265.

Ramík, J., & Korviny, P. (2010). Inconsistency of pair-wise comparison matrix with fuzzy elements based on geometric mean. *Fuzzy Sets and Systems*, *161*(11), 1604–1613.

Refsgaard, J. C., Van der Sluijs, J. P., Højberg, A. L., & Vanrolleghem, P. (2005). Harmoni-CA Guidance—Uncertainty analysis. Retrieved from: http://www.harmoni-ca.info/toolbox/docs/Harmoni-ca_Guidance_1_Uncertainty_Analysis.pdf, 05.08.2016

Reichert, P., Langhans, S. D., Lienert, J., & Schuwirth, N. (2015). The conceptual foundation of environmental decision support. *Journal of Environmental Management*, *154*, 316–332.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475.

Rousseeuw, P., Struyf, A., & Hubert, M. (2014). Cluster analysis extended Rousseeuw et al. Retrieved from: http://cran.r-project.org/web/packages/available_packages_by_name.html, 10.08.2016

Saaty, T. L. (1986). Axiomatic foundation of the analytic hierarchy process. *Management Science*, *32*(7), 841–855.

Saaty, T. L. (1995). *Decision making for leaders—The analytic hierarchy process for decisions in a complex world* (Third (extensively revised) ed.). Pittsburg: RWS Publications.

Saaty, T. L. (1996). *Multicriteria decision making—The analytic hierarchy process—Planning, priority setting, resource allocation* (Paperback (2nd ed.). Pittsburg: RWS Publications.

Saaty, T. L. (1999). Basic theory of the analytic hierarchy process: How to make a decision. *Revista de la Real Academia de Ciencias Exactas, Físicas y Naturales*, *93*(4), 395–423.

Saaty, T. L. (2007). Time dependent decision-making; dynamic priorities in the AHP/ANP: Generalizing from points to functions and from real to complex variables. *Mathematical and Computer Modelling*, *46*(7–8), 860–891.

Saaty, T. L. (2010). *Principia mathematica decernendi—Mathematical principles of decision making—Generalization of the analytic network process to neural firing and synthesis*. Pittsburg: RWS Publications.

Saaty, T. L., & Begicevic, N. (2010). The scope of human values and human activities in decision making. *Applied Soft Computing*, *10*(4), 963–974.

Saaty, T. L., & Ozdemir, M. S. (2003). Why the magic number seven plus or minus two. *Mathematical and Computer Modelling*, *38*(3), 233–244.

Saaty, T. L., & Peniwati, K. (2013). *Group decision making: Drawing out and reconciling differences*. Pittsburg: RWS Publications.

Saaty, T. L., & Tran, L. T. (2007). On the invalidity of fuzzifying numerical judgments in the analytic hierarchy process. *Mathematical and Computer Modelling*, *46*(7–8), 962–975.

Saaty, T. L., & Vargas, L. G. (1984). The legitimacy of rank reversal. *Omega*, *12*(5), 513–516.

Saaty, T. L., & Vargas, L. G. (1993). Experiments on rank preservation and reversal in relative measurement. *Mathematical and Computer Modelling*, *17*(4–5), 13–18.

Saaty, T. L., & Vargas, L. G. (2012). The possibility of group choice: Pairwise comparisons and merging functions. *Social Choice and Welfare*, *38*, 481–496.

Sadiq, R., & Tesfamariam, S. (2009). Environmental decision-making under uncertainty using intuitionistic fuzzy analytic hierarchy process (IF-AHP). *Stochastic Environmental Research and Risk Assessment*, *23*(1), 75–91.

Salo, A. A., & Hämäläinen, R. P. (1997). On the measurement of preferences in the analytic hierarchy process. *Journal of Multi-Criteria Decision Analysis*, *6*, 309–319.

Schmoldt, D. L. (2001). *The analytic hierarchy process in natural resource and environmental decision making*. Heidelberg: Springer.

Scholz, R. W., & Binder, C. R. (2011). *Environmental literacy in science and society: From knowledge to decisions*. Cambridge: Cambridge University Press.

Srdjevic, B., & Srdjevic, Z. (2013). Synthesis of individual best local priority vectors in AHP-group decision making. *Applied Soft Computing*, *13*, 2045–2056.

Srdjevic, B., Srdjevic, Z., & Blagojevic, B. (2014). First-level transitivity rule method for filling in incomplete pair-wise comparison matrices in the analytic hierarchy process. *Applications of Mathematics*, *8*(2), 459–467.

Stam, A., & Duarte Silva, A. P. (2003). On multiplicative priority rating methods for the AHP. *European Journal of Operational Research*, *145*(1), 92–108.

Stewart, T., French, S., & Rios, J. (2013). Integrating multicriteria decision analysis and scenario planning—Review and extension. *Omega*, *41*(4), 679–688.

Sugihara, K., & Tanaka, H. (2001). Interval evaluations in the analytic hierarchy process by possibility analysis. *Computational Intelligence*, *17*(3), 567–579.

Toth, H. (1999). Towards fixing some 'fuzzy' catchwords: A terminological primer. In L. Zadeh, & J. Kacprzyk (Eds.), *Computing with words in information/intelligent systems 1* (Vol. 33) (pp. 154–179). Heidelberg: Physica-Verlag HD (Springer).

Toth, W., Wolfslehner, B., &Vacik, H. (2014). A comprehensive uncertainty analysis of the analytic hierarchy process in the context of environmental decision making, ISAHP 2014 (pp. 5). Washington D.C.

Triantaphyllou, E. (2001). Two new cases of rank reversals when the AHP and some of its additive variants are used that do not occur with the multiplicative AHP. *Journal of Multi-Criteria Decision Analysis*, *10*(1), 11–25.

Triantaphyllou, E., & Sanchez, A. (1997). A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. *Decision Sciences*, *28*(1), 151–194.

Vacik, H., Kurttila, M., Hujala, T., Khadka, C., Haara, A., Pykäläinen, J., … Tikkanen, J. (2014). Evaluating collaborative planning methods supporting programme-based planning in natural resource management. *Journal of Environmental Management*, *144*, 304–315.

Vacik, H., & Lexer, M. J. (2001). Application of a spatial decision support system in managing the protection forests of Vienna for sustained yield of water resources. *Forest Ecology and Management*, *143*(1–3), 65–76.

Von Solms, S. (2011). Validity of the AHP/ANP: Comparing apples and oranges. *International Journal of the Analytic Hierarchy Process*, *3*(1).

Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M. B. A., Janssen, P., … Krayer von Krauss, M. P. (2003). Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, *4*(1), 5–17.

Warren, L. (2004). Uncertainties of the analytic hierarchy process. Retrieved from: http://www.dsto.defence.gov.au/publications/3476/DSTO-TN-0597.pdf, 10.02.2015: Australian Government - Department of Defence.

Warren, L. (2006). Structural uncertainties in numerical induction models. Retrieved from: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA460088, 10.08.2016: Australian Government - Department of Defence.

Webber, S. A., Apostolou, B., & Hassell, J. M. (1997). The sensitivity of the analytic hierarchy process to alternative scale and cue presentations. *European Journal of Operational Research*, *96*(2), 351–362.

Wedley, W. C. (1990). Combining qualitative and quantitative factors—An analytic hierarchy approach. *Socio-Economic Planning Sciences*, *24*(1), 57–64.

Wedley, W. C. (1993). Consistency prediction for incomplete AHP matrices. *Mathematical and Computer Modelling*, *17*(4–5), 151–161.

Whitaker, R. (2007). Criticisms of the analytic hierarchy process: Why they often make no sense. *Mathematical and Computer Modelling*, *46*(7–8), 948–961.

Wolfslehner, B., & Vacik, H. (2011). Mapping indicator models: From intuitive problem structuring to quantified decision-making in sustainable forest management. *Ecological Indicators*, *11*(2), 274–283.

Wolfslehner, B., Vacik, H., & Lexer, M. J. (2005). Application of the analytic network process in multi-criteria analysis of sustainable forest management. *Forest Ecology and Management*, *207*(1–2), 157–170.

Zeshui, X., & Cuiping, W. (1999). A consistency improving method in the analytic hierarchy process. *European Journal of Operational Research*, *116*(2), 443–449.

Zhang, Q. (1998). Fuzziness-vagueness-generality-ambiguity. *Journal of Pragmatics*, *29*(1), 13–31.

Zhü, K. (2014). Fuzzy analytic hierarchy process: Fallacy of the popular methods. *European Journal of Operational Research*, *236*(1), 209–217.

How to cite this article: Toth W, Vacik H. A comprehensive uncertainty analysis of the analytic hierarchy process methodology applied in the context of environmental decision making. *J Multi-Crit Decis Anal*. 2018;25:142–161. https://doi.org/10.1002/mcda.1648

8.3 Publication III

Sustainability Science
https://doi.org/10.1007/s11625-021-01009-7

SPECIAL FEATURE: ORIGINAL ARTICLE

Synergies and Trade-offs between Sustainable Development Goals and Targets

Deepening our understanding of which policy advice to expect from prioritizing SDG targets: introducing the Analytic Network Process in a multi-method setting

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Received: 18 March 2021 / Accepted: 12 July 2021

Abstract

The indivisibility principle of the 2030 Agenda is considered key for the implementation of policies in pursuit of the Sustainable Development Goals (SDGs). Therefore, science is not only asked to develop new methods for assessing SDG target interactions but also to translate findings of methodological insights into policy advice for easy take-up by policymakers. The present paper demonstrates how to adopt the multi-criteria analysis technique Analytic Network Process (ANP) for prioritizing SDG targets in considering all positive and possible indirect SDG target interactions at once. The application of the ANP is linked to a multi-method setting embracing positive scores derived from the analytical methods Nilsson-scale, a cross-impact matrix, and network analysis techniques. This supports the prioritization of SDG targets when considering *n*-order neighbours in a network with respect to their synergies. The ANP allows evaluating the synergistic potential and progress controllability of SDG target rankings calculated by CI-matrix metrics and thus provides conclusions on the importance of *n*-order interactions of SDG targets in a network for the final ranking. We showed that the application of a combination of different analytical methods improves the overall quality of the formulated policy advice regarding its scope and methodological profoundness. In this context, we compared the analytical methods involved with respect to their ability to formulate policy advice and finally presented a framing how to translate methodological results into concrete and applicable policy advice.

Keywords Sustainable Development Goals (SDGs) · SDG target ranking · Analytic Network Process (ANP) · Cross-impact matrix · Network analysis · Policy advice

Introduction

SDG implementation in the context of indivisibility

The 2030 Agenda was adopted by the UN General Assembly in 2015. Its fundamental aim is to transform the world to a sustainable development path while leaving no one behind (United Nations 2015), and this ethos is fundamentally linked to the Agenda's two key principles: universality and indivisibility. Universality implies that the Agenda applies to all nations regardless of their levels of income. Indivisibility means that the formulated 17 Sustainable Development Goals (SDGs) should be implemented as an 'indivisible whole'. This interconnected nature of the SDGs is seen as axiomatic, even though the connections between the goals are uneven or that economic growth is prioritised over ecological integrity (Eisenmenger et al. 2020; McGowan et al. 2019).

On a political level, it is emphasized that it is currently unclear how to translate the indivisibly connected SDGs and their interactions into concrete efforts that support SDG goal achievement: most governments are not effectively able to simultaneously deal with multi-sectoral, multi-scale, and multi-actor issues created by the indivisible nature of the SDGs. In particular, it remains unclear how existing policies, instruments, and institutions will or even can adapt to meet

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the SDGs (Collste et al. 2017; Gusmão Caiado et al. 2018; Kanie et al. 2019).

Therefore scientists developed a huge variety of concepts, guidelines, and frameworks as what to governments must consider while implementing the SDGs: Sachs et al. (2019) proposed six major transformations to coordinate SDG interventions and concluded that policy coherence is needed across the various branches of government and between levels of government to guide these transformations. In this regards a proposed action agenda for science recommends the development of new tools that help to identify and quantify SDG target interactions as well as monitoring mechanisms to ensure sustainability transformation within the thresholds of the global planetary boundaries (Allen et al. 2021; Lu et al. 2015). Alternatively, Weitz et al. (2015) proposed the adoption of an integrated "biophysical nexus" using, for example, a water, energy and food nexus as the starting point for planning SDG implementation. Bowen et al. (2017) recommend three concerted efforts to address key governance challenges, with the first involving the fostering of collective action and the second to identify tensions between the simultaneous goal attainment of different SDGs and to address these trade-offs within SDG implementation. The third aspect of Bowen et al. (2017)'s plan is to ensure accountability for commitments made by various nations. Stafford-Smith et al. (2017) argue for realizing synergies in the SDG implementation, meaning to strive for action that supports the attainment of multiple goals at the same time. Furthermore, they highlight the necessity to integrate SDG implementation across industrial sectors, with societal actors, and in a manner that includes low-, medium- and high-income countries. In a similar vein, Lusseau and Mancini (2019) concluded that SDG targets should be contextualised because trade-offs differ according to country-income levels. The International Council for Science (2017) called for more coherence during the implementation of several SDGs, whether that be to overcome administrative silos or to more comprehensively consider SDGs interactions. Miola et al. (2019) developed two dashboards which combination allows to integrate "agreed" SDG interlinkages from literature with policy priority areas to develop policy implementation strategies. Reviewing the national implementation experience in 26 countries, Allen et al. (2018) concluded that key gaps appear because of missing interaction assessments between SDG targets (including both trade-offs and synergies). The implementation of the SDGs thus requires the identification of policy actions that maximise preferred policy outcomes through targeting the interactions inherent to the SDGs.

What drives the need for this type of multi-faceted research is the requirement to facilitate an integrated and coherent manner of SDG implementation derived from the UN's focus on 'the indivisible whole approach' (United Nations 2015). However, the 'indivisible whole approach' as a conceptual basis has not yet been comprehensively interpreted by the scientific community (Bennich et al. 2020). Against this background, scientists are being asked to translate the growing understanding of SDG interactions into usable policy advice and make this knowledge readily available for policymakers (Breuer et al. 2019; United Nations 2015). In their review article, Bennich et al. (2020) classified the literature concerning targeted policy challenges and analytical methods applied as well as a number of other categories. Based on this, they identify several policy challenges describing policy-relevant questions the scientific community has responded to so far. The perspective of highlighting the potential to formulate policy advice created by analytical methods and the latter's ability to address specific policy challenges is still lacking.

Facilitating the analysis of SDG target interactions with the Analytic Network Process

SDG implementation is most often assessed by using one or a necessary sequence of analytical methods to evaluate SDG (target) interactions of single case studies. Bennich et al. (2020) report in their review that 37% of the considered publications report a multi-method approach indicating the application of more than one method. A closer look at these publications shows that specific bundles of methods were used in a combined way. A common multi-method application embraces a scoring based on the seven-point scale conceptualisation of Nilsson et al. (2016) (Nilsson-scale), the collection of this data in a cross-impact matrix (CI-matrix) allowing to derive SDG target rankings and also other network analyses based on the data arranged in the CI-matrix. However, applying single analytical methods only for a specific step of the necessary methods' sequence excludes the possibility to learn from the pros and cons of different approaches. Only one article reports the application of different analytical methods being applied for prioritising SDG targets thus far (Allen et al. 2019). Evidence from this study points to the fact that the use of different approaches when assessing a given single case leads to different results and can potentially lead to different or even contradictory policy advice.

As previously said, how best to implement the SDGs raises the question of where to start. Accordingly, Breuer et al. (2019) proposed a roadmap for integrated SDG implementation where the first step is the definition of an issue-based entry point into the network of SDG interdependencies, in particular, to prioritise SDG implementation action (e.g. decide to focus interventions on SDG target 1.1). The issue of ranking SDGs or SDG targets is seen as critical because it involves inherent moral and ethical ramifications (Breuer et al. 2019; Pongiglione 2015). Only 20% of recent studies have concerned themselves with prioritisation attempts (Bennich et al. 2020). However, in other sustainability contexts, the ranking of management alternatives using multi-criteria analysis approaches is a well-elaborated research area (e.g.: Cinelli et al. 2014; Kandakoglu et al. 2019; Mendoza and Martins 2006; Toth and Vacik 2018; Vacik et al. 2014).

SDG target prioritisation attempts have already been published considering trade-offs and synergies jointly. For example, Weitz et al. (2018) ranked SDG targets according to their net influence (the total influence of a single SDG target on all other SDG targets considering the second-order neighbours) and how SDG targets are, in turn, influenced by others. Additionally, the authors state: "The question arises how deep into the network and chain of influence the assessment should go; is it worthwhile to also account for third-order neighbours and beyond?" (Weitz et al. 2018, 542). Scott et al. (2017) surveyed 85 experts from several governmental and non-governmental institutions asking the question: which 20 of these 117 SDG targets should be tackled as part of a multi-year effort to fulfil all of the SDGs? A more recent study used an online consultation process for stakeholders that targeted 167 representatives, primarily from the private sector in Switzerland. As a result, the study identified 33 priority SDG targets by combining all the stakeholders' responses and different statistical measures (Breu et al. 2020). Allen et al. (2019) used a multi-criteria approach, in particular, a weighted linear average to integrate results from 3 criteria ('level of urgency', 'systemic impact', and 'policy gap') to prioritise SDG targets. Additionally, they compared SDG target rankings derived from different analytical approaches (e.g., CI-matrix and network analysis measures) with respect to a single case study. There are arguments for handling positive and negative SDG target interactions separately as this might support a more in-depth analysis of the systemic role of the SDGs (Breu et al. 2020; Pham-Truffert et al. 2020). Furthermore, the application of analytical methods in a multi-method setting can provide benefits even if negative SDG target interactions are neglected (Allen et al. 2019).

The noted gaps in research can be addressed by applying the Analytic Network Process (ANP). The ANP is a multi-criteria analysis technique and the generalised form of the better-known Analytic Hierarchy Process (AHP). While the AHP is centred on the decision problem in a hierarchy, the ANP generalises the hierarchy into a network to better capture real-world interdependencies and processes. The ANP facilitates the decomposition of a decision problem into a network of its single elements to reduce the overall complexity. Further, the ANP provides the opportunity to consider the dependence of these elements and capture the feedback of the elements that often arise in practical decision-making. Feedback in this context involves cycles, which can lead to an infinite process. The result of the ANP calculations is a prioritisation of the system's elements with respect to the included clusters composed of system elements (usually criteria and alternatives) and the overall defined goal (Saaty and Vargas 2013). The ANP allows also to integrate different views and value pluralism for developing policy advice (Mulligan 2013; Munda 2019; Saaty and Vargas 2013) and is not limited to subjective qualitative evaluations such as scores; in particular, it allows to process various numerical data and empirical measurements as well (Adams and Saaty 1999; Saaty and Vargas 2013). The ANP has been applied in a diverse range of areas in the last few decades (Kheybari et al. 2020; Sipahi and Timor 2010) on topics entailing all three pillars of sustainable development. This includes business and financial management topics (economic pillar), issues of environment and energy management (environmental pillar) and questions of human resources management (social pillar) (Kheybari et al. 2020). Its application with respect to the SDGs which would thereby simultaneously integrate all the dimensions of sustainability has still not been undertaken. Therefore, we will demonstrate how to use the ANP for prioritising SDG targets according to their synergies and at the same time linking it to a multi-method setting embracing positive scores derived from the Nilsson-scale, the CI-matrix and network analysis. Furthermore, we will study if the consideration of third-order neighbours and beyond makes a difference in the evaluation of SDG target interactions to meet the indivisible whole requirement.

The paper is organised as follows: "Material and methods" presents the application of the ANP and all necessary steps in the data preparation and analysis. Section "Results" details the results of the application of the ANP to a case study in a multi-method setting and "Discussion" discusses the opportunities and limitations of the approach to draw some conclusions in "Conclusions and further research".

Materials and methods

Methodological approach

To ensure that the description of the methodological approach of the multi-method setting is also readily perceivable for any reader—and perhaps not a specialist in the field of multi-criteria analysis techniques—we refer to a hypothetical SDG target network that serves as a simplified demonstration of the approach and follow the best practice checklist for ANP reporting (Mu et al. 2020). Hence, the reader is guided through the development of the (1) SDG target network model (see "Model development, evaluation question and rating scales") and (2) the development of the unweighted and the weighted supermatrix (see "Reporting the unweighted and weighted supermatrix"). Upon this basis, (3) the limit supermatrix containing the SDG target rankings is computed (see "Computation of the limit supermatrix (SDG target ranking)"). The application was performed using the free software product Super Decisions v.3.2.0 (SuperDecisions 2019a).

Model development, evaluation question and rating scales

The SDG targets serve as nodes in the ANP model and are contained in one inner-dependent cluster, meaning that all of the cluster's nodes only depend on elements of this cluster. For the SDG targets (nodes) that show an interaction, links were established within the model to allow the integration of the respective SDG target interaction data. With respect to the hypothetical example, the SDG target network consists of six SDG targets (see ANP model in Fig. 1).

The common AHP/ANP application and its measurement procedure rely on data input that originates from a pairwise comparison of system elements using a pairwise-comparison matrix. In the hypothetical example, this would mean comparing the interaction of two SDG targets with respect to another single SDG target. As shown in the pairwise-comparison matrix concerning SDG target 1.1 in Fig. 1a, SDG target 15.1 demonstrates an interaction with SDG target 1.1 that is 1.5 times larger than the interaction of SDG target 1.3 with SDG target 1.1. Qualitatively and using the Saaty-scale, the interaction of SDG target 15.1 with SDG target 1.1 is 'equally to moderately more' larger than the interaction of SDG target 1.3 with SDG target 1.1 (Saaty and Vargas 2013). Conducting such a pairwise-comparison of all the system elements with respect to each other for each SDG target would lead to six pairwise-comparison matrices, concerning the single SDG targets 1.1, 1.2, 1.3., 15.1, 15.2 and 15.3. This is shown with two exemplary matrices in Fig. 1a. Pairwise-comparisons allow consideration of the otherwise intangible (unmeasurable) relationship between two elements in the ANP. Based on the pairwise comparisons matrices, priority vectors can be calculated that include the relative 'importance' of the elements with respect to the single element they are compared to. These normalised priority vectors would then be collected in the unweighted supermatrix for further calculations (Saaty and Vargas 2013) (Fig. 1a).

However, the elicitation of the input data used for the application of the ANP to our case study follows a different procedure. The data is gathered using the Nilsson-scale asking the question ''If progress is made on target *x* (rows), how does this influence progress on target *y* (columns)?''. As the underlying mathematics of the ANP relies only on positive values we only can use the positive interaction scores in our application. Two models were built, considering (1) the influence from a single SDG target on all other SDG targets and (2) from the perspective of a single SDG target, the influence received from all other SDG targets. For demonstration purposes, and with respect to the hypothetical SDG target network, only the model considering the influence from a single SDG target on all other SDG targets is presented (Fig. 1b).

All SDG interaction scores are then collected in a CI-matrix which shows the network under consideration and contains all the elements listed horizontally and vertically (Weitz et al. 2018). Hence, the CI-matrix is identical to the

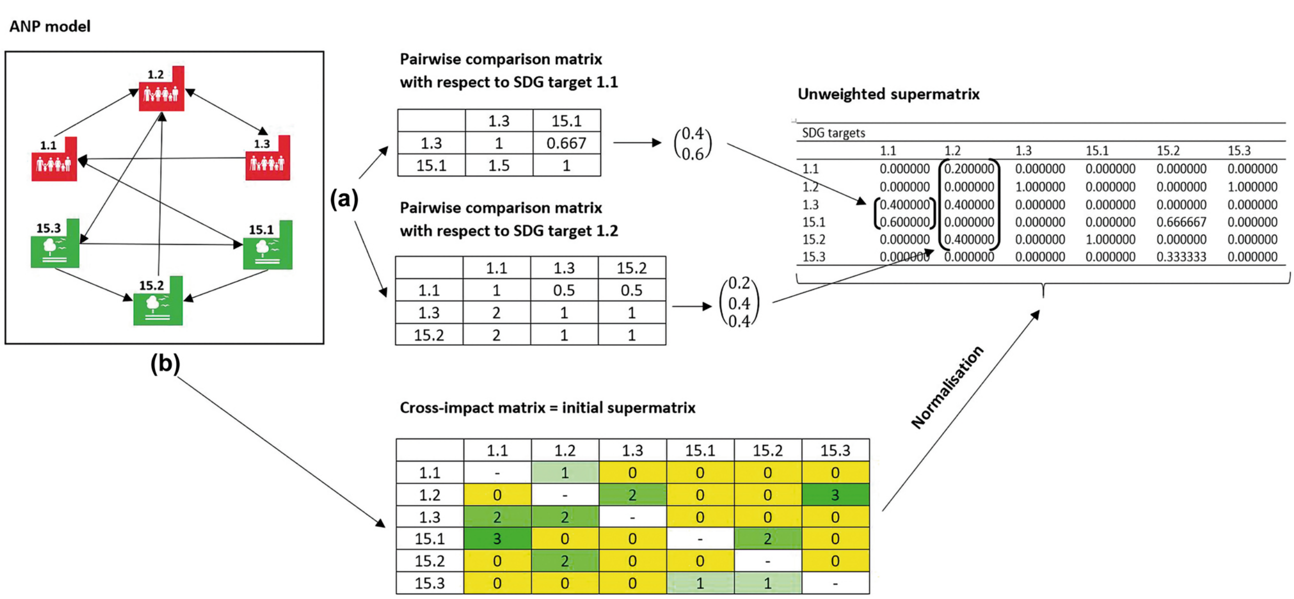

Fig. 1. Hypothetical example: ANP model development and data input. **a** Data input for the ANP using pairwise comparison matrices **b** Data input for the ANP using Nilsson scores of the CI-matrix as direct data

initial supermatrix of the ANP (Saaty and Vargas 2013). The referring quantitative scores were subsequently put into the ANP model using the direct data entry mode in Super Decisions v.3.2.0 instead of the common pairwise comparisons and were therefore collected in the initial supermatrix (Fig. 1b) (Adams and Saaty 1999) to derive the unweighted supermatrix.

Consistency

The consistency check is an essential process step and usually applied instrument to prove if two corresponding scores (e.g. SDG target 1.3 directly influences SDG target 1.5 and SDG target 1.5 directly influences SDG target 1.3) in the initial supermatrix are logical in terms of the goodness or "harmony" of the two pairwise comparisons in the context of the total network (Bozóki and Rapcsák 2008). However, as we entered the data directly into the model and did not use pairwise comparisons, there was no need for the consistency check in our research. Nevertheless, the scores do not need to be consistent or even transitive to be further computed using the ANP (Saaty 1990).

Reporting the unweighted and weighted supermatrix

To elicit the priorities given in the scored SDG target interactions which were collected in the initial supermatrix, the local priorities (intermediate step to calculate the final priorities) for each SDG target are calculated by normalising their referring columns of the initial supermatrix, i.e., by calculating the relative influence of the SDG targets that summed up to 1 (see Fig. 1b). In other words, only the influence with respect to the direct SDG targets' neighbours is considered in this step (1st order influence). For the columns including only one interaction (SDG target 1.3, SDG target 15.1 and SDG target 15.3), the normalisation procedure leads to the inclusion of these single SDG target with the relative influence of 1, regardless of their differences in the original score.

The unweighted supermatrix is accordingly composed of these normalised local priorities of all single SDG targets (Saaty and Vargas 2013; SuperDecisions 2019b). As there is only one cluster used for modelling the SDG target network, no further calculations using weights for different clusters are needed as the unweighted and weighted supermatrices are identical (see supplementary material). For the hypothetical example, the weighted supermatrix is presented in Table 1.

To ensure that the weighted supermatrix is valid to calculate the limit supermatrix (final step to calculate SDG target rankings), we have tested the convergence of the weighted supermatrix with respect to the proposed heuristic of Mu et al. (2020) using R (R Development Core Team 2014). This means, that it is first checked to see if absorbing nodes exist in the network, indicating that a single node receives influence while not influencing other nodes. Additionally, confirmation is made that the columns of the weighted supermatrix are column-stochastic and therefore composed of normalised priority vectors. Absorbing nodes, as well as a non-column-stochastic weighted supermatrix, leads to a limit supermatrix primarily composed of zeros. Secondly, the weighted supermatrix is checked to see if sufficient links among the nodes are given to prevent the weighted supermatrix fragmenting into smaller subnetworks when calculating the limit supermatrix (Mu et al. 2020). The test result shows that the weighted supermatrix of the hypothetical example is suitable for the task at hand.

Computation of the limit supermatrix (SDG target ranking)

Theoretically, considering all indirect SDG target interactions for any case requires a self-multiplication sequence of weighted supermatrices W that tends to cycle to infinity: the weighted supermatrix itself, its square, its cube, etc., denoted by W^k where $k = 1, 2, \ldots, \infty$. However, to consider all possible indirect SDG target interactions for a specific case involves a search for the limit of that particular sequence. Therefore, the primary goal is to obtain the limit supermatrix by raising the weighted supermatrix to powers by multiplying it times itself until the limit of $W^{n+1} = W^n$ is reached, indicating that the next powers do not add any detail to the result. For the weighted supermatrix, including a cyclic graph, to be relevant for the indivisibly connected SDG target networks, the average influence along all possible

Table 1 Hypothetical example: weighted supermatrix

SDG targets						
	1.1	1.2	1.3	15.1	15.2	15.3
1.1	0.000000	0.200000	0.000000	0.000000	0.000000	0.000000
1.2	0.000000	0.000000	1.000000	0.000000	0.000000	1.000000
1.3	0.400000	0.400000	0.000000	0.000000	0.000000	0.000000
15.1	0.600000	0.000000	0.000000	0.000000	0.666667	0.000000
15.2	0.000000	0.400000	0.000000	1.000000	0.000000	0.000000
15.3	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000

indirect SDG target interactions up to a given length is provided by the Cesaro sum $\lim_{k\to\infty} \frac{1}{N} \sum_{k=1}^{N} W^k$, where N is the limit of the sequence of the weighted supermatrices raised to powers (Rokou et al. 2012; Saaty 1999; Saaty and Vargas 2013; Sava et al. 2020; SuperDecisions 2019b).

When all the columns are identical, the limit supermatrix is converged into a stable matrix and the self-multiplication of the weighted supermatrix is halted. Hence, the limit supermatrix contains the SDG target ranking as the final priorities in each column (see supplementary material).

The rationale behind raising the weighted supermatrix to powers is to allow the SDG target network to be represented as a graph in the ANP and permit all direct and indirect SDG target interactions to be considered. Each transition within the network from one SDG target to the next is represented by the corresponding power of the weighted supermatrix. In other words, the power of the weighted supermatrix corresponds to the orders of influence considered within the SDG target network. As the limit N of the sequence of the weighted supermatrices raised to powers is not returned by Super Decisions v.3.2.0, we call this the n-order influence. This is captured by the corresponding sequence of weighted supermatrices W^k where $k=N$. With respect to the hypothetical example, the process of raising the weighted supermatrix to powers is conceptually shown with the systemic understanding of the SDG target interactions in Fig. 2. The 1st order influence refers to the sequence of weighted supermatrices W^k where $k=1$, the 2nd order influence refers to W^k where $k=2$, the 3rd order influence refers to W^k where $k=3$ and finally for the n-order influence W^k where $k=N$.

The columns of the limit supermatrix then establish the final priorities for the SDG targets. With respect to the hypothetical example, SDG target 15.2 is ranked best due to its highest influence on all other SDG targets in the network (Table 2), while considering the 1st order influence, SDG target 1.2 and 15.1 are ranked best (see largest row sum in the cross-impact matrix in Fig. 1b).

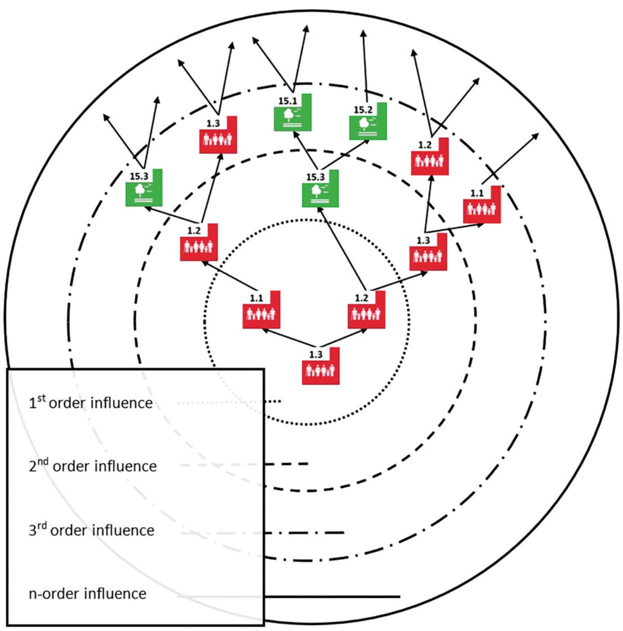

Fig. 2 Hypothetical example: a systemic understanding of SDG target interactions. Credit (SDG icons): United Nations

Sensitivity analysis

As we only used the ANP mathematics to calculate SDG target rankings, no decision alternatives and criteria are included in the ANP model and hence no sensitivity analysis can be performed regarding the effect on the prioritisation of alternatives.

Application to a case study

SDG target rankings in Weitz et al (2018)

The application of the ANP in a multi-method setting is demonstrated on the case study data presented in Weitz et al. (2018). The study analysed the interactions of 34 SDG targets to rank them according to their synergistic potential and with respect to their control over its own progress for Sweden. The study was chosen because of its available dataset, its comprehensive description of the analytical methods applied and its transparently constructed policy advice.

Table 2 Hypothetical example: limit supermatrix

SDG targets						
	1.1	1.2	1.3	15.1	15.2	15.3
1.1	0.040650	0.040650	0.040650	0.040650	0.040650	0.040650
1.2	0.203252	0.203252	0.203252	0.203252	0.203252	0.203252
1.3	0.097561	0.097561	0.097561	0.097561	0.097561	0.097561
15.1	0.235772	0.235772	0.235772	0.235772	0.235772	0.235772
15.2	0.317073	0.317073	0.317073	0.317073	0.317073	0.317073
15.3	0.105691	0.105691	0.105691	0.105691	0.105691	0.105691

Re-calculation of SDG target rankings based on the CI-matrix

The application of the ANP to this case study data stringently followed all methodological steps examined with the hypothetical example as described in "Methodological approach". The test result with respect to the proposed heuristic of Mu et al. (2020) shows that the weighted supermatrix of the country case study is suitable for the task at hand. For applying the ANP in a multi-method setting embracing positive scores derived from the Nilsson-scale, the CI-matrix, and network analysis, it is necessary to ensure that identical input data sets are used. Hence, as the ANP only allows processing positive interaction scores, the two SDG target rankings (synergistic potential and progress control based on the CI-matrix) are re-calculated after deleting those SDG target interactions that show a negative interaction score (see Fig. 3).

This procedure allows aligning the CI-matrix SDG target rankings with the ANP SDG target rankings. The re-calculation was done as follows: firstly, the total influence of the SDG targets on the second-order network was re-calculated as: $I_i^{\mathrm{Total}} = D_i^{\mathrm{Out}} + \frac{1}{2}\sum_{j \neq i} I_{ij} D_j^{\mathrm{Out}}$, where D_i^{Out} is the out-degree of target i, I_{ij} is the interaction score of target i that influences target j and, finally, D_i^{Out} is the out-degree of target j. Of note here is the fact that the out-degree of a single SDG target is equal to its row-sum in the cross-impact matrix. Secondly, the SDG target ranking concerned with the total influence receiving from all other SDG targets with respect to the first-order network was re-calculated by taking the column-sum in the cross-impact matrix for each SDG target.

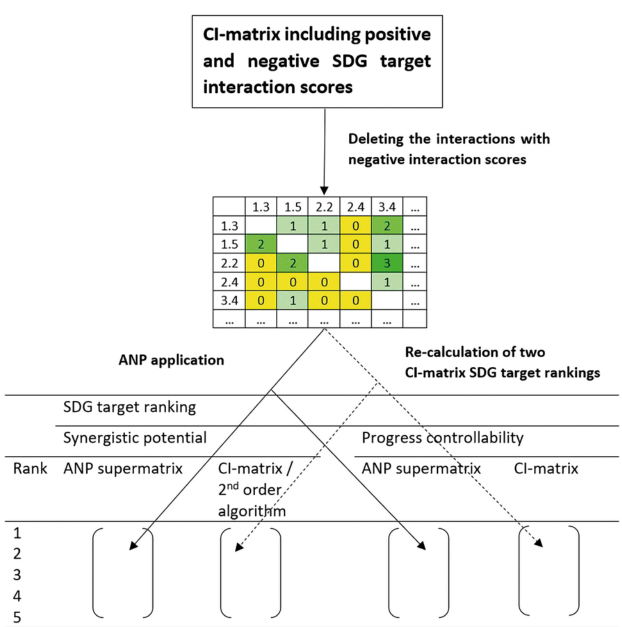

Fig. 3 Overall approach for re-calculation of SDG target rankings

Results

Application of the Analytic Network Process

As indicated in "Model development, evaluation question and rating scales", two ANP models were employed to compute two SDG target rankings, the first ranking sorts the SDG targets with respect to their synergistic potential, i.e., due to their overall positive influence on all other SDG targets in the SDG target network. The second ranking orders the SDG targets regarding their control over their own progress, i.e., due to the positive influence received from all the other SDG targets in the SDG target network. The relative importance or priority of the SDG targets is shown in Table 3. The higher the priority, the better the rank. Regarding the progress controllability ranking it is important to note here, that a high overall level of influence received from all other SDG targets suggests that less control is inherent to the SDG target regarding its own progress, i.e., the worst ranked SDG target is the most preferred one in this context. The complete results of the re-calculations of the SDG target rankings of the Weitz et al. (2018) country case are part of the published supplementary materials.

Since the main research question was to understand whether it makes an empirical difference to account for 3rd order influence and beyond in SDG target networks in fulfilment of the indivisible whole idea, the authors team was encouraged to check if it makes a difference to consider more indirect SDG target interactions beyond the 2nd order influences when elaborating SDG target rankings. Therefore, the ANP was applied to analyse the *n*-order influence of the SDG target network. Table 4 compares the top 5 ranked SDG targets of the re-calculated CI-matrix/2nd order algorithm and the ANP for the two rankings for the case study data.

Overall, it can be seen that the ANP results are close to both SDG target rankings calculated by the CI-matrix approaches. The top-ranked SDG target is the same for each of the two rankings. For the rankings concerning the synergistic potential, the ANP ranks SDG target 8.5 4th, whereas it is not part of the top 5 derived from the CI-matrix/2nd order algorithm, where it is ranked 8th. Also of note is the fact that SDG target 9.5 is ranked 6th applying the ANP. With respect to the rankings concerned with the progress controllability, the ANP ranks SDG target 15.5 4th and SDG target 6.6 5th, whereas neither are included in the top 5 rankings calculated by the CI-matrix/2nd order algorithm. SDG target 15.5 is ranked 7th by the CI-matrix/2nd order algorithm and SDG target 4.4 is 12th. Conversely, the CI-matrix/2nd order algorithm place SDG target 13.2 and SDG target 12.1 in the top 5, whereas they are ranked 11th and 8th, respectively by the ANP.

Deepening our understanding which policy advice to expect

Analytical methods' potential to formulate policy advice

In considering the analytic dimension of the applied methods, we are evaluating their potential to formulate policy advice and to which policy challenges (Bennich et al. 2020) the policy advice can respond to. As shown in Table 5, the results of the various analytical methods provide a different perspective on the potential policy advices. The CI-matrix, the supermatrix of the ANP as well as network analysis methods produce results that respond to the policy challenge of 'policy prioritisation' as they are instruments guiding the identification of the most promising entry point into the network of SDG interdependencies. Furthermore, the network analysis methods allow the identification of political actors that are responsible for the achievement of specific SDG targets and hence the prioritisation of such institutions' stakeholder collaboration. Additionally, they create results that respond to the policy challenge 'integrated perspective' in the sense of promoting systemic thinking and learning of the involved decision-makers.

The ANP supermatrix and the CI-matrix allow calculating the same two SDG target rankings (synergistic potential, and progress controllability) (see Table 5). Weitz et al. (2018) argue that the calculation of the influence of single SDGs considering only direct SDG target interactions provides insufficient information to effectively guide priority-setting of SDG implementation action. Both CI-matrix approaches (CI-matrix and CI-matrix/2nd order algorithm) presented provide a ranking to the synergistic potential of the SDG targets differing only in their order of influence within the SDG target network that is considered (Table 5). The CI-matrix/2nd order algorithm method also processes indirect SDG target interactions by referring to the 2nd order influence and is, therefore, a more suitable SDG target ranking as the one provided by the classical CI-matrix because it includes a better information base. As with the two CI-matrix approaches, the ANP allows the ranking of SDG targets due to their synergistic potential. The ANP calculates the positive influence of the *n*-order SDG target network (see "Computation of the limit supermatrix (SDG target ranking)"), which allows the processing of more indirect SDG target interactions and leading to a more sensitive SDG target ranking, that might change when additional interactions are introduced to the network. Therefore, to guide policy-making on how to approach the SDGs without losing the indivisible whole idea, we argue that the ANP is more suitable to identify possible entry points of the SDG network than the two CI-matrix approaches. Additionally, both, the CI-matrix approach relying on the 1st order influence, as well as the ANP, provide guidance regarding whether progress on an SDG target is at risk of being neutralised or halted by progress on other SDG targets. The results of the SDG target rankings indicate the control possible over the SDG targets' progress. Translating this into policy advice means that actual SDG implementation should focus on those SDG targets that are largely autonomous, when it comes to their own progress as this significantly reduces the randomness of outcomes of any realised SDG implementation actions.

The network analysis methods presented allow to identify and to prioritize stakeholder collaboration as well as enhanced system understanding for policymakers. The identified sub-networks support the detection of influence paths within the SDG target network allowing to consider

Table 3 ANP results: SDG target rankings

Rank	Synergistic potential		Progress controllability	
	SDG target	Priority	SDG target	Priority
1	16.6	0.067946	1.5	0.065546
2	8.4	0.060716	13.1	0.052345
3	12.1	0.060336	2.4	0.049379
4	8.5	0.045566	15.5	0.046410
5	12.5	0.043292	6.6	0.041714
6	9.5	0.042887	10.1	0.040204
7	4.4	0.042869	8.5	0.037492
8	5.5	0.041932	12.1	0.037234
9	9.4	0.040456	15.2	0.037073
10	7.3	0.037740	6.5	0.034224
11	13.1	0.036779	13.2	0.033470
12	13.2	0.035138	1.3	0.033240
13	1.5	0.034357	8.4	0.032216
14	1.3	0.034000	4.4	0.029821
15	11.2	0.032496	9.4	0.029552
16	16.4	0.031316	10.7	0.029033
17	2.4	0.029822	3.4	0.028803
18	5.4	0.028510	11.2	0.026900
19	7.2	0.028324	11.1	0.026388
20	6.5	0.026843	14.1	0.026053
21	4.1	0.025938	5.5	0.024441
22	10.7	0.017785	12.5	0.023927
23	11.1	0.017195	2.2	0.023540
24	2.2	0.016783	17.13	0.022874
25	17.13	0.016736	14.4	0.021721
26	15.5	0.015570	7.3	0.020780
27	14.4	0.015274	3.8	0.019732
28	14.1	0.014927	16.6	0.018545
29	10.1	0.014226	9.5	0.018408
30	15.2	0.010882	5.4	0.018029
31	3.8	0.009571	4.1	0.016756
32	17.11	0.009246	7.2	0.014747
33	6.6	0.008726	16.4	0.012182
34	3.4	0.005818	17.11	0.007223

Table 4 Comparison of top 5 ranked SDG targets of the re-calculated CI-matrix/2nd order algorithm and the ANP with respect to different SDG target rankings

	SDG target ranking			
	Synergistic potential		Progress controllability	
Rank	ANP supermatrix	CI-matrix / 2nd order algorithm	ANP supermatrix	CI-matrix
1	16.6	16.6	1.5	1.5
2	8.4	12.1	13.1	2.4
3	12.1	8.4	2.4	13.1
4	8.5	12.5	15.5	13.2
5	12.5	9.5	6.6	12.1

Colour indicates whether the SDG target is ranked identically for both SDG interaction analysis approaches (green), the SDG target is included in the top 5 of both approaches (cyan) or not (red)

cost efficiency reflections of SDG implementation at a very basic level. Goal attainment of a specific SDG target may be approached by various influence paths embracing differing SDG targets that trigger this influence path. Therefore, several SDG implementation actions may be chosen to approach these different SDG targets which, in turn, reveal that the costs of a single SDG implementation action become a relevant factor for implementation planning. Approaching clusters of 'positive mutual influence' allows the identification of areas where success can be rapidly achieved regarding SDG goal attainment, while also revealing the negative links (trade-offs) between clusters that are crucial elements within the network. Additionally, the political actors playing a role within these clusters can be better identified as stakeholders and may build strategic partnerships (Weitz et al. 2018).

Improving the overall quality of the policy advice

The combination of different analytical methods comprises advantages and disadvantages in their ability to improve the quality of the provided policy advice, which raises the question of a suitable setting. Policy advice being generically formulated in terms of the "potential" insights and improvements from a methodological point of view is inadequate to guide policymaking for a specific situation. Translating the analytical methods' results into concrete policy advice needs to consider one of the four basic types of advice that can be given to decision-makers: 'Recommend For', Recommend Against' and 'Decision Support/Information' (Dalal and Bonaccio 2010).

'**Recommend For**' is the typical conceptualisation of advice in the decision-making literature. In the context of SDG implementation, it could be the advice for choosing a specific SDG target as an entry point of the SDG target network or a recommendation for stakeholder collaboration. In the context of the case study application, a policy advice could be formulated: 'Start SDG implementation by approaching **SDG target 16.6** (*Effective institutions*)', because it best supports the positive interactions in the SDG target network'. Relying on the SDG target rankings produced by the ANP provides a more solid information base, as it includes more indirect SDG target interactions, than the rankings provided by the CI-matrix methods. SDG target 16.6 is identified by the ANP as the target with the highest synergistic potential in the whole network (Table 4). Conversely, '**Recommend Against**' could help to identify SDG targets that should be perhaps not prioritized in a specific SDG implementation due to their less control over their own progress (e.g., SDG target 1.5 in the progress controllability ranking, Table 3).

The advices '**Decision Support**' and '**Information**' supplement the decision-making process by providing information about the interactions of a specific SDG target within a network and by recommending different procedures regarding how to decide where to start SDG implementation. In the context of the case study application a policy advice could be formulated: 'Compare the implementation costs of **SDG target 16.6** (*Effective institutions*) and **SDG target 16.4** (*illicit financial/arms flow*)', because there might be different preferable compromises of implementation costs and direct/indirect approaching of SDG target 16.6. In particular, the influence paths in the sub-network of indivisible interactions indicate to compare the implementation costs for SDG target 16.4 and SDG target 16.6 as they have a bidirectional influence on each other and as it might be that the indirect support for SDG target 16.6 through an SDG implementation option targeting SDG target 16.4 is cheaper as the implementation option directly approaching SDG target 16.6. Furthermore, for these two SDG targets their inherent control over their own progress based on the ANP results could be taken into consideration when starting the SDG implementation. In the context of the case study example a policy advice could be formulated: 'Consider the inherent control over their own progress of **SDG target 16.6**

Table 5 Potential of the analytical methods to formulate policy advice

Policy challenges	Results and policy advice	Analytical method
Policy prioritisation	**SDG target ranking—synergistic potential** Approximation of issue-based entry point into the network of SDG interdependencies	**CI-matrix** The SDG targets can be ranked by their overall positive influence on all other SDG targets considering the 1st order influence in the SDG target network
		CI-matrix/2nd order algorithm The SDG targets are ranked by their overall positive influence on all other SDG targets considering 2nd order influence in the SDG target network (Weitz et al. 2018)
		ANP supermatrix The SDG targets can be ranked by their overall positive influence on all other SDG targets considering the *n*-order influence in the SDG target network
	SDG target ranking—progress controllability Identification of SDG targets that show overall low control over their own progress	**CI-matrix** The SDG targets can be ranked by the overall positive influence received from all other SDG targets considering the 1st order influence in the SDG target network
		ANP supermatrix The SDG targets can be ranked by the overall positive influence received from all other SDG targets considering the n-order influence in the SDG target network
	Visualisation Identification and prioritisation of stakeholder collaboration	**Network analysis** The identification and prioritisation of stakeholder collaboration can be supported by visualizing the direct influence from and on other SDG targets from the perspective of a single SDG target
Policy prioritisation and integrated perspective	**SDG target clusters of 'positive mutual influence'** Identification of the cluster's stakeholder and prioritisation of referring collaboration. Enhancing the system understanding	**Network analysis** Using network analysis software for the identification of clusters of 'positive mutual influence', i.e., the SDG targets included show mostly synergies
Integrated perspective	**Sub-networks of indivisible and constraining/counteracting interactions** Enhancing the system understanding by identifying effective SDG targets and influence paths	**Network analysis** The sub-networks (of indivisible and constraining/counteracting interactions) help to focus on those SDG target interactions that are important due to their multiple and strong influence on other SDG targets

(*Effective institutions*) and **SDG target 16.4** (*illicit financial/arms flow*)', because relatively less inherent control can introduce randomness of outcomes of realised SDG implementation actions. A high overall level of influence received from all other SDG targets suggests that less control is inherent to the SDG target regarding its own progress. Hence, it is easier to achieve these heavily influenced SDG targets by ensuring the achievement of those SDG targets that exert a positive interaction.

The SDG target ranking showing the progress controllability (Table 3) suggests that this dimension could be neglected in our application as both SDG targets are almost similar ranked with respect to their control over their own progress (SDG target 16.6 is ranked 28th and SDG target 16.4 33th).

Network analysis methods allow to visualize the importance of actors in a network from the perspective of a single SDG target. This can help to identify and prioritize stakeholders with whom collaboration can be beneficial. In the context of the case study example and if SDG target 16.6 is chosen to be approached directly, the framing as concrete policy advice could be as follows: 'Analyse if progress on **SDG target 16.6** (*Effective institutions*) may impede the progress of other SDG targets or if progress on other SDG targets may prevent progress on **SDG target 16.6** (*Effective institutions*)', because there might be resistance or the need to negotiate. In this context, the collaboration with those actors that are responsible for the achievement of specific SDG targets can help to improve the coordination process or can lead to a dilution of the desired implementation effects.

Referring to our case study application, these simplified examples demonstrate that the combination of different analytical methods improves the overall quality of the formulated policy advice regarding its scope and methodological profoundness. Additionally, the presented framing of methodological results as concrete advice may allow enhancing the to foster accepting and utilising it (Bonaccio and Dalal 2006; Dalal and Bonaccio 2010).

Discussion

Recent literature addresses policy challenges and gaps applicable to SDG implementation (Allen et al. 2018; Bennich et al. 2020). This has come about, at least in part, because scientists are now not only asked to develop new tools and methods for evaluating SDG target interactions but also to translate methodological results of SDG interaction analysis approaches into relevant policy advice to inform and guide SDG implementation in response to these policy challenges and gaps. This is a difficult task as the 'methodological profoundness' of such advice inherently depends on the methodological understanding of the approach used and of its limitations. The ANP addresses many of the limitations of current approaches as listed by Ospina-Forero et al. (2020). It is easily scalable, i.e. enlargeable by additional factors, because it employs the software tool Super Decisions, an established and well-known product (SuperDecisions 2019a). The replicability of ANP application is given as the applied methods used for score elicitation as well as the subsequent steps to use this data to build an SDG target network are transparently and comprehensively described in the present study. The ANP model can be built for every region or country separately and thus allows a consideration of the socio-economic context in terms of their specific SDG target interactions. Additional contextual factors, such as good data availability are a prerequisite for the application of the ANP, which may not be given for countries in transition or developing countries. Additionally, the ANP allows a consideration of the directionality of the SDG target interactions, because its mathematics is based on graph theory. The validity of the ANP's mathematical foundation has been widely discussed in the literature and there is broad agreement about its' soundness in the scientific community (Toth and Vacik 2018; Whitaker 2007a, b). However, if more IT-based and highly mathematical models, such as the ANP, are applied to elaborate on policy advice, more expertise is needed to understand the black box 'software' and its related modelling assumptions. Hence, translating these methodological results into practice relevant advice is highly dependent on how methodological uncertainty is addressed which, if done well, may increase the likelihood that the advice will be taken up by policymakers (Brugnach et al. 2007; Gilbert et al. 2018).

The ANP allows to assess SDG target interactions by considering all possible indirect SDG target interactions. A limitation is related to the ANP mathematics, which relies on positive values only and needs to exclude negative values from SDG target interactions and hence neglects SDG target trade-offs. The re-calculation of the CI-matrix SDG target ranking concerned with the synergistic potential and relying on the 2nd order algorithm shows that the top nine ranked SDG targets of the second-order network presented in Weitz et al. (2018) are identical and in the same order as the respective rankings in the re-calculation. From a methodological perspective, this is evidence that neglecting a small share of negative interactions (8% negative interactions compared to the positive ones) may not change the overall SDG target ranking, at least that held true for the case presented here. Generally speaking, an SDG interaction analysis approach covering the best possible information base should allow processing the quantification of all positive and negative SDG target interactions. Furthermore, in doing so, it should also cover all the influence paths including all direct and indirect SDG target interactions within and among SDGs. Such an understanding may guide the directed development of new tools and methods for evaluating SDG target interactions considering these methodological properties.

Current SDG implementation literature is primarily concerned with the conceptualisation of SDG (target) interactions (Bennich et al. 2020), although some authors have now begun addressing the understanding that SDG implementation action can be better optimised to support goal-attainment of different SDG (targets) simultaneously (Alcamo et al. 2020; Scharlemann et al. 2020). Hence, a methodological approach supporting SDG implementation should not only be able to evaluate SDG target interactions, but also be able to assess SDG implementation actions with respect to their direct influence on different SDG targets. This highlights that developing *ex-ante* policy evaluations should take place in the first step of making the complex computational task of calculating SDG target rankings. The ANP could support this easily based on its supermatrix, which allows to simply extend the model by including SDG implementation action beneath SDG targets.

Analytical methods can be evaluated in several ways. Ospina-Forero et al. (2020) developed broad, desirable qualities embracing scalability, replicability, specificity and directionality that should be adhered to by the second generation of SDG network estimation techniques and we recommend building upon them as additional comparison attributes. This is similar to what is discussed by Breuer et al. (2019), who reflected on several methodological limitations of the current approaches and highlighted the need for replicability, context-sensitivity (which matches with the specificity attribute of Ospina-Forero et al. (2020)) as well as the ability to rank SDG targets to formulate concrete policy advice for specific situations. Alcamo et al. (2020) presented the four characteristics of (1) Level of external data requirements, (2) Level of expert judgement, (3) Interactive and (4) Spatially explicit results to compare methods used for analysing SDG interactions in different case studies. Several differences can be identified among the approaches depending on the underlying evaluation aspects, however, a broad and systematic assessment of current methods and tools is still lacking. We focused on the potential to formulate policy advice as attributes to promote a better understanding of the analytical methods' properties and thus contribute to further close this gap.

All the presented SDG target rankings were initially based on data measured with Nilsson's seven-point scale (Nilsson et al. 2016), a mechanism which is not meant to measure the strength of SDG target interactions (Nilsson 2017). This indicates that the policy advice given are relative statements and not statements proffering absolute influence of SDG targets on one another. In particular, the results of any SDG interaction analysis approach relying on the Nilsson scale can only be interpreted with respect to the initial semantic meaning of the score, that is to say, the relative ability to make progress on a single SDG target depending on the progress of interacting SDG targets of the SDG target network (Nilsson 2017). For example, the best-ranked SDG target with respect to the synergistic potential is the one that best supports the positive interactions within the SDG target network. From a goal attainment perspective, and considering the group of SDG network estimation methods relying on the Nilsson-scale, it leaves the question open of how to measure the absolute interaction dynamic of an entire SDG target network in the sense of a flow and stock conceptualisation for SDG indicator analysis. In particular, a positive interaction between two SDG targets is not conclusive evidence of how these two perform with respect to indicators and how progress on one SDG target improves this indicator's performance.

Additionally, the CI-matrix SDG target rankings are based on the calculation of a net-influence that do not reflect the distribution between weak and strong SDG targets nor the diversification of positive and negative SDG target interactions, all of which may 'dilute' the perception of potential trade-offs (Pham-Truffert et al. 2020; Weitz et al. 2018). Thus, a recent publication handles positive and negative SDG target interactions separately to develop a more distinguished classification of the systemic role of the SDGs (Pham-Truffert et al. 2020). A more distinct integration of the distribution of weak and strong SDG targets as well as of the diversification of positive and negative SDG target interactions into an evaluation may well improve the quality of the SDG target rankings concerned with progress controllability. The knowledge which distribution, respectively diversification is better than another may help to reduce the randomness of outcomes of realised SDG implementation actions. In this context, Pham-Truffert et al. (2020) highlighted that SDG targets may "buffer" systemic effects by having more weight from incoming rather than outgoing ties. Focusing SDG implementation action on SDG targets that have less inherent control over their own progress, as well as on "buffer" SDG targets, may hinder the unfolding of positive multiplication effects within an SDG target network.

The ANP validates both re-calculated SDG target rankings initially based on the CI-matrix in terms of approving the best-ranked SDG target, which indicates that these rankings are robust. The consideration of third-order neighbours and beyond makes a difference for the ranks 4–5 (see "Application of the Analytic Network Process") of the presented top 5 ranked SDG targets (Table 4), as they are not identically ranked for both the re-calculated SDG target rankings and the ANP. Allen et al. (2019) report a high degree of consistency across the rankings they compared, in the sense that seven of the top ten ranking targets were the same across the four different methods. However, the four methods lead to three different top ranked SDG targets. Another difference to our study, and what is acknowledged by the authors, is, that they neglected a minority (12% negative interactions compared to the positive ones) of negative interactions applying network analysis methods. As there is no systematic comparison of 2nd order SDG target rankings with the n-order rankings as derived from the ANP, this result may not hold true in the context of other case studies. Important to note here, is the fact, that the priorities of the 3 top-ranked SDG targets considering the synergistic potential (16.6, 8.4 and 12.1) (Table 3) are very similar, indicating that small uncertainties regarding the interaction scoring could change the best-ranked SDG target. This procedure—applying several methodological approaches to a single country case study may contribute to overcoming the formulated impossibility of comprehensive validation tests for SDG target rankings (Ospina-Forero et al. 2020).

We identified influence paths within the SDG target network which provides the possibility to optimise the costs of SDG implementation actions. This is in a similar vein to Pham-Truffert et al. (2020) who presented positive self-reinforcing sub-networks that may serve as "cycle" orientated policy interventions. Nevertheless, the costs of SDG implementation actions may still be dependent on the particular SDG target that is being pursued.

With respect to the presented influence path of our case in the multi-method setting, costs may vary depending upon whether effective institutions (SDG target 16.6) are approached or whether an investment to prevent illicit financial and arms flow is planned (SDG target 16.4). This suggests then that the identification of cost-effective actions implementing SDGs inherently depends on the understanding of an SDG network and its related influence paths. Therefore, evaluations of SDG implementation actions cannot be separated from an improved system analysis of the SDG target interactions within the network. This is in line with the Independent Group of Scientists (2019) who emphasised that issue-based entry points should be used to address the underlying network of SDG interdependencies. Additionally, choosing SDG implementation actions that function as synergy driver supporting different goals simultaneously may also save financial resources in the long term (Alcamo et al. 2020). Also, policy actors have an important role in the implementation process, as they have different capacities and power to influence the uptake of SDGs on national, local or even multiple scales in different temporal dimensions. This can have an influence on policy development and the identification of cost-effective actions for implementing SDGs as well.

As the synergies and trade-offs of SDG target interactions are highly context-dependent (Lusseau and Mancini 2019; Warchold et al. 2020), costs for a specific SDG implementation action, such as 'establishing effective institutions', may vary from country to country depending on circumstances. However, from a methodological perspective, there is still space for improvement regarding the restrictions of single influence paths concerning cost-efficiency. Orientating on assessable management entities, such as sub-networks and influence-paths, is both pragmatic and supports the identification of readily undertakable steps for implementing SDGs but fundamentally conflicts with the aim to consider all indirect SDG target interactions. Indeed, restricting influence paths would necessitate that indirect SDG target interactions are deliberately neglected.

However, given the increasing amount of research on methods and the number of tools available for evaluating SDG target interactions, there is the need to locate the methodological perspective presented here in a broader context, such as in a structured framework or process enhancing the coherence of policymaking for the 2030 agenda (Breu et al. 2020; Nilsson and Weitz 2019).

Conclusions and further research

The present paper demonstrates how to use the ANP for prioritising SDG targets in a multi-method setting embracing positive scores derived from the Nilsson-scale, the CI-matrix, and network analysis. The additional application of the ANP allowed deepening the understanding of how the overall quality of the policy advice can be improved. By putting the methodological dimension of the analytical methods under the spotlight, we are able to classify their potential to formulate policy advice and to identify to which policy challenges the policy advice responds to. Additionally, we present how methodological results derived could be framed as concrete policy advice to support its applicability for the policy process with respect to a specific case.

As shown, the ANP allows consideration of all the positive and possible indirect SDG target interactions and, as such, can quantify "how target interactions ripple through the complete network, i.e., going beyond second-order interactions" (Weitz et al. 2018, 547). Obviously, a major future research question should focus on how to consider negative SDG target interactions as well in applying the ANP. The following items could be considered as starting point: (1) To handle positive and negative SDG target interactions separately and to develop an aggregated network analysis similar to recent publications (Breu et al. 2020; Pham-Truffert et al. 2020), (2) to design a mechanism and translate the positive and negative single interactions into positive preference values. This is similar to the fundamental thought to invert cost values into positive preferences as presented by Saaty (1996). Finally, (3) mathematical solutions to extend the ANP mathematics itself could be elaborated on. Another future research could develop an understanding which conditions of case studies allow to neglect a small share of negative SDG target interactions and support the application of the ANP and thus profit from the opportunity to compute all feed-back loops. Our methodological approach highlights a more general need, namely to develop a conceptional framework of the 'SDG implementation system' to allow systematic *ex-ante* evaluations of SDG implementation actions: first of all in this regard, such a framework should embrace an understanding of the different estimation procedures of SDG (target) interactions (Ospina-Forero et al. 2020), their ability to quantify the number of orders of both positive and negative influence as well as direct and indirect SDG target interactions. Furthermore, the estimation procedures' point of intersection for measuring and governing goal attainment by using relevant (composite) indicators should be specified (Diaz-Sarachaga et al. 2018; Hák et al. 2016; Lyytimäki et al. 2020a, b). Secondly, the framework should include an understanding of how SDG implementation actions trigger single or numerous SDG targets and subsequently the whole SDG target network by activating their various indirect influences. Thirdly, it should also take into account an understanding of how to evaluate synergies and trade-offs, separately and in a synthesized form within and across boundaries linking national attempts to the global development agenda (Forestier and Kim 2020; Zhao et al. 2021). Finally, the newly envisioned framework needs to be shared with scientists, policymakers and the public (Bain et al. 2019) to support a societal discourse about realisable SDG implementation actions.

However, from a methodological point of view, systematic *ex-ante* evaluations of SDG implementation actions based on a shared 'conceptual SDG implementation framework' can only be elaborated upon by applying a combination of different methods and tools highlighting their advantages and disadvantages, in particular with respect to their potential to formulate policy advice. This indicates the need to elaborate an in-depth understanding of current methodological approaches to guide the choice toward the best multi-method application for approaching specific cases as well as their related policy challenges and gaps concerned with SDG implementation (Allen et al. 2018; Bennich et al. 2020; Vacik et al. 2014). However, to avoid 'paralysis by analysis', where the different methodological results remain unused, scientists will be required to develop new tools and methods that satisfy policymakers' needs (Allen et al. 2021; Lyytimäki et al. 2020a, b). The knowledge created and the experiences gathered while implementing SDGs using these approaches should then be made available to scientists, policymakers, and the public on a central web-based knowledge platform such as that presented by Nilsson et al. (2018). This allows the embedding of the current advances in methodological development and related application experience into a larger process of collaborative and transdisciplinary science-policy-public learning for implementing the 2030 agenda.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-021-01009-7.

Acknowledgements Open access funding was provided by the University of Natural Resources and Life Sciences Vienna (BOKU).

Funding Open access funding provided by University of Natural Resources and Life Sciences Vienna (BOKU).

References

Adams WJL, Saaty R (1999) SuperDecisions Software Guide. www.superdecisions.com

Alcamo J, Thompson J, Alexander A, Antoniades A, Delabre I, Dolley J et al (2020) Analysing interactions among the sustainable development goals: findings and emerging issues from local and global studies. Sustain Sci 15(6):1561–1572. https://doi.org/10.1007/s11625-020-00875-x

Allen C, Metternicht G, Wiedmann T (2018) Initial progress in implementing the Sustainable Development Goals (SDGs): a review of evidence from countries. Sustain Sci. https://doi.org/10.1007/s11625-018-0572-3

Allen C, Metternicht G, Wiedmann T (2019) Prioritising SDG targets: assessing baselines, gaps and interlinkages. Sustain Sci 14(2):421–438. https://doi.org/10.1007/s11625-018-0596-8

Allen C, Metternicht G, Wiedmann T (2021) Priorities for science to support national implementation of the sustainable development goals: a review of progress and gaps. Sustain Dev. https://doi.org/10.1002/sd.2164

Bain PG, Kroonenberg PM, Johansson L-O, Milfont TL, Crimston CR, Kurz T et al (2019) Public views of the Sustainable Development Goals across countries. Nat Sustain 2(9):819–825. https://doi.org/10.1038/s41893-019-0365-4

Bennich T, Weitz N, Carlsen H (2020) Deciphering the scientific literature on SDG interactions: a review and reading guide. Sci Total Environ 728:138405. https://doi.org/10.1016/j.scitotenv.2020.138405

Bonaccio S, Dalal RS (2006) Advice taking and decision-making: an integrative literature review, and implications for the organizational sciences. Organ Behav Hum Decis Process 101(2):127–151. https://doi.org/10.1016/j.obhdp.2006.07.001

Bowen KJ, Cradock-Henry NA, Koch F, Patterson J, Häyhä T, Vogt J, Barbi F (2017) Implementing the "Sustainable Development Goals": towards addressing three key governance challenges—collective action, trade-offs, and accountability. Curr Opin Environ Sustain 26–27:90–96. https://doi.org/10.1016/j.cosust.2017.05.002

Bozóki S, Rapcsák T (2008) On Saaty's and Koczkodaj's inconsistencies of pairwise comparison matrices. J Global Optim 42(2):157–175

Breu T, Bergöö M, Ebneter L, Pham-Truffert M, Bieri S, Messerli P et al (2020) Where to begin? Defining national strategies for implementing the 2030 Agenda: the case of Switzerland. Sustain Sci. https://doi.org/10.1007/s11625-020-00856-0

Breuer A, Janetschek H, Malerba D (2019) Translating sustainable development goal (SDG) interdependencies into policy advice. Sustainability 11(7):2092

Brugnach M, Tagg A, Keil F, de Lange WJ (2007) Uncertainty matters: computer models at the science-policy interface. Water

Resour Manage 21(7):1075–1090. https://doi.org/10.1007/s11269-006-9099-y
Cinelli M, Coles SR, Kirwan K (2014) Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol Ind 46:138–148. https://doi.org/10.1016/j.ecolind.2014.06.011
Collste D, Pedercini M, Cornell SE (2017) Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. Sustain Sci 12(6):921–931
Dalal RS, Bonaccio S (2010) What types of advice do decision-makers prefer? Organ Behav Hum Decis Process 112(1):11–23. https://doi.org/10.1016/j.obhdp.2009.11.007
Diaz-Sarachaga JM, Jato-Espino D, Castro-Fresno D (2018) Is the Sustainable Development Goals (SDG) index an adequate framework to measure the progress of the 2030 Agenda? Sustain Dev 26(6):663–671. https://doi.org/10.1002/sd.1735
Eisenmenger N, Pichler M, Krenmayr N, Noll D, Plank B, Schalmann E et al (2020) The Sustainable Development Goals prioritize economic growth over sustainable resource use: a critical reflection on the SDGs from a socio-ecological perspective. Sustain Sci 15(4):1101–1110. https://doi.org/10.1007/s11625-020-00813-x
Forestier O, Kim RE (2020) Cherry-picking the Sustainable Development Goals: Goal prioritization by national governments and implications for global governance. Sustain Dev 28(5):1269–1278. https://doi.org/10.1002/sd.2082
Gilbert N, Ahrweiler P, Barbrook-Johnson P, Narasimhan KP, Wilkinson H (2018) Computational modelling of public policy: reflections on practice. J Artif Soc Soc Simul 21(1):14. https://doi.org/10.18564/jasss.3669
Gusmão Caiado RG, Leal Filho W, Quelhas OLG, de Mattos L, Nascimento D, Ávila LV (2018) A literature-based review on potentials and constraints in the implementation of the sustainable development goals. J Clean Prod 198:1276–1288. https://doi.org/10.1016/j.jclepro.2018.07.102
Hák T, Janoušková S, Moldan B (2016) Sustainable development goals: a need for relevant indicators. Ecol Ind 60:565–573. https://doi.org/10.1016/j.ecolind.2015.08.003
Independent Group of Scientists appointed by the Secretary-General (2019) Global sustainable development report 2019: the future is now—science for achieving sustainable development. United Nations, New York. https://sustainabledevelopment.un.org/content/documents/24797GSDR_report_2019.pdf. Accessed 22 July 2021
International Council for Science (2017) A guide to SDG interactions: from science to implementation. International Council for Science, Paris
Kandakoglu A, Frini A, Ben Amor S (2019) Multicriteria decision making for sustainable development: a systematic review. J Multi-Criteria Decis Anal 26(5–6):202–251. https://doi.org/10.1002/mcda.1682
Kanie N, Griggs D, Young O, Waddell S, Shrivastava P, Haas PM et al (2019) Rules to goals: emergence of new governance strategies for sustainable development. Sustain Sci 14(6):1745–1749. https://doi.org/10.1007/s11625-019-00729-1
Kheybari S, Rezaie FM, Farazmand H (2020) Analytic network process: an overview of applications. Appl Math Comput 367:124780. https://doi.org/10.1016/j.amc.2019.124780
Lu Y, Nakicenovic N, Visbeck M, Stevance A-S (2015) Policy: five priorities for the UN sustainable development goals. Nature 520(7548):432–433. https://doi.org/10.1038/520432a
Lusseau D, Mancini F (2019) Income-based variation in sustainable development Goal interaction networks. Nat Sustain 2(3):242–247. https://doi.org/10.1038/s41893-019-0231-4
Lyytimäki J, Lonkila K-M, Furman E, Korhonen-Kurki K, Lähteenoja S (2020a) Untangling the interactions of sustainability targets: synergies and trade-offs in the Northern European context. Environ Dev Sustain. https://doi.org/10.1007/s10668-020-00726-w
Lyytimäki J, Salo H, Lepenies R, Büttner L, Mustajoki J (2020b) Risks of producing and using indicators of sustainable development goals. Sustain Dev 28(6):1528–1538. https://doi.org/10.1002/sd.2102
McGowan PJK, Stewart GB, Long G, Grainger MJ (2019) An imperfect vision of indivisibility in the Sustainable Development Goals. Nat Sustain 2(1):43–45. https://doi.org/10.1038/s41893-018-0190-1
Mendoza G, Martins H (2006) Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. For Ecol Manage 230(1):1–22
Miola A, Borchardt S, Neher F, Buscaglia D (2019) Interlinkages and policy coherence for the Sustainable Development Goals implementation: an operational method to identify trade-offs and co-benefits in a systemic way. Retrieved from Publications Office of the European Union. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC115163/sdg_interlinkages_jrc115163_final_on_line.pdf
Mu E, Cooper O, Peasley M (2020) Best practices in analytic network process studies. Expert Syst Appl 159:113536. https://doi.org/10.1016/j.eswa.2020.113536
Mulligan M (2013) Models supporting decision-making and policy evaluation. Environ Model Find Simplicity Complex Second Edn. https://doi.org/10.1002/9781118351475.ch20
Munda G (2019) Multi-criteria Evaluation in Public Economics and Policy. In: Doumpos M, Figueira JR, Greco S, Zopounidis C (eds) New perspectives in multiple criteria decision making - innovative applications and case studies. Springer Nature Switzerland AG, Cham, Switzerland, pp 297–313
Nilsson M (2017) Important interactions among the sustainable development—goals under review at the high-level political forum 2017. http://www.jstor.com/stable/resrep02837. Accessed 22 July 2021
Nilsson M, Weitz N (2019) Governing trade-offs and building coherence in policy-making for the 2030 Agenda. Polit Governance 7(4):10. https://doi.org/10.17645/pag.v7i4.2229
Nilsson M, Griggs D, Visbeck M, Skolan för arkitektur och s, Hållbar utveckling m o t, Kth, Miljöstrategisk a (2016) Map the interactions between Sustainable Development Goals. Nature 534(7607):320
Nilsson M, Chisholm E, Griggs D, Howden-Chapman P, McCollum D, Messerli P et al (2018) Mapping interactions between the sustainable development goals: lessons learned and ways forward. Sustain Sci. https://doi.org/10.1007/s11625-018-0604-z
Ospina-Forero L, Castañeda G, Guerrero OA (2020) Estimating networks of sustainable development goals. Inf Manag. https://doi.org/10.1016/j.im.2020.103342
Pham-Truffert M, Metz F, Fischer M, Rueff H, Messerli P (2020) Interactions among Sustainable Development Goals: Knowledge for identifying multipliers and virtuous cycles. Sustain Dev 28(5):1236–1250. https://doi.org/10.1002/sd.2073
Pongiglione F (2015) The need for a priority structure for the Sustainable Development Goals. J Glob Ethics 11(1):37–42. https://doi.org/10.1080/17449626.2014.1001912
R Development Core Team (2014) R: a language and environment for statistical computing and graphics, Software version 3.5.1. R Foundation for Statistical Computing, Vienna. http://www.r-project.org/
Rokou E, Kirytopoulos K, Voulgaridou D (2012) Analytic network process demystified. Paper presented at the International Federation for Infomation Processing (IFIP) Working Group 8.3: Decision Support Systems, Greece
Saaty TL (1990) How to make a decision: the analytic hierarchy process. Eur J Oper Res 48(1):9–26

Saaty TL (1996) The analytic network process. RWS Publications, Pittsburgh
Saaty TL (1999) Fundamentals of the Analytic Network Process. Paper presented at the ISAHP 1999, Kobe
Saaty TL, Vargas LG (2013) Decision making with the analytic network process: economic, political, social and technological applications with benefits, opportunities, costs and risks. Springer, New York
Sachs JD, Schmidt-Traub G, Mazzucato M, Messner D, Nakicenovic N, Rockström J (2019) Six transformations to achieve the Sustainable Development Goals. Nat Sustain 2(9):805–814. https://doi.org/10.1038/s41893-019-0352-9
Sava MG, Vargas LG, May JH, Dolan JG (2020) Multi-dimensional stability analysis for analytic network process models. Ann Oper Res. https://doi.org/10.1007/s10479-020-03553-4
Scharlemann JPW, Brock RC, Balfour N, Brown C, Burgess ND, Guth MK et al (2020) Towards understanding interactions between Sustainable Development Goals: the role of environment–human linkages. Sustain Sci 15(6):1573–1584. https://doi.org/10.1007/s11625-020-00799-6
Scott S, Leitner J, Hynes W (2017) Where to start with the SDGs? Retrieved from OECD. https://oecd-development-matters.org/2017/07/20/where-to-start-with-the-sdgs. Accessed 22 July 2021
Sipahi S, Timor M (2010) The analytic hierarchy process and the analytic network process: an overview of applications. Manag Decis 48(5):775–808
Stafford-Smith M, Griggs D, Gaffney O, Ullah F, Reyers B, Kanie N et al (2017) Integration: the key to implementing the sustainable development goals. Sustain Sci 12(6):911–919. https://doi.org/10.1007/s11625-016-0383-3
SuperDecisions (2019a) SuperDecisions v 3.2.0. Creative Decision Foundation. https://www.superdecisions.com/downloads/
SuperDecisions (2019b) Tutorial in complex decision models (ANP). Retrieved from https://www.superdecisions.com/sd_resources/v28_man04.pdf. Accessed 3 Aug 2019
Toth W, Vacik H (2018) A comprehensive uncertainty analysis of the analytic hierarchy process methodology applied in the context of environmental decision making. J Multi-Criteria Decis Anal 25(5–6):142–161. https://doi.org/10.1002/mcda.1648
United Nations (2015) Transforming our world: the 2030 Agenda for Sustainable Development A/RES/70/1. The General Assembly, New York
Vacik H, Kurttila M, Hujala T, Khadka C, Haara A, Pykäläinen J et al (2014) Evaluating collaborative planning methods supporting programme-based planning in natural resource management. J Environ Manage 144:304–315. https://doi.org/10.1016/j.jenvman.2014.05.029
Warchold A, Pradhan P, Kropp JP (2020) Variations in sustainable development goal interactions: population, regional, and income disaggregation. Sustain Dev. https://doi.org/10.1002/sd.2145
Weitz N, Nilsson M, Davis M (2015) A nexus approach to the post-2015 agenda: formulating integrated water, energy, and food SDG. SAIS Rev Int Aff 34(2):37–50
Weitz N, Carlsen H, Nilsson M, Skånberg K (2018) Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustain Sci 13(2):531–548. https://doi.org/10.1007/s11625-017-0470-0
Whitaker R (2007a) Criticisms of the analytic hierarchy process: why they often make no sense. Math Comput Model 46(7–8):948–961. https://doi.org/10.1016/j.mcm.2007.03.016
Whitaker R (2007b) Validation examples of the analytic hierarchy process and analytic network process. Math Comput Model 46(7–8):840–859. https://doi.org/10.1016/j.mcm.2007.03.018
Zhao Z, Cai M, Wang F, Winkler JA, Connor T, Chung MG et al (2021) Synergies and tradeoffs among Sustainable Development Goals across boundaries in a metacoupled world. Sci Total Environ 751:141749. https://doi.org/10.1016/j.scitotenv.2020.141749

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8.3.1 Supplementary materials

8.3.1.1 Results of ANP application: Supermatrices

ANP results: Influence on all other SDG targets: unweighted supermatrix = weighted supermatrix

	T1_3	T1_5	T2_2	T2_4	T3_4	T3_8	T4_1	T4_4	T5_4	T5_5	T6_5	T6_6	T7_2	T7_3	T8_4
T1_3	0.000000	0.026316	0.055556	0.000000	0.095238	0.066667	0.066667	0.083333	0.133333	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000
T1_5	0.074074	0.000000	0.055556	0.000000	0.047619	0.066667	0.066667	0.083333	0.066667	0.066667	0.000000	0.043478	0.000000	0.000000	0.000000
T2_2	0.000000	0.052632	0.000000	0.000000	0.142857	0.000000	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.074074
T2_4	0.000000	0.000000	0.000000	0.000000	0.047619	0.000000	0.000000	0.000000	0.000000	0.000000	0.095238	0.086957	0.000000	0.055556	0.037037
T3_4	0.000000	0.026316	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000
T3_8	0.074074	0.052632	0.055556	0.000000	0.095238	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T4_1	0.037037	0.052632	0.000000	0.000000	0.047619	0.066667	0.000000	0.125000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T4_4	0.074074	0.052632	0.000000	0.030303	0.047619	0.066667	0.066667	0.000000	0.000000	0.066667	0.000000	0.000000	0.083333	0.000000	0.037037
T5_4	0.111111	0.026316	0.166667	0.030303	0.095238	0.133333	0.133333	0.125000	0.000000	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000
T5_5	0.111111	0.026316	0.111111	0.060606	0.142857	0.133333	0.200000	0.041667	0.133333	0.000000	0.047619	0.000000	0.000000	0.000000	0.000000
T6_5	0.000000	0.052632	0.000000	0.060606	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.130435	0.000000	0.000000	0.037037
T6_6	0.000000	0.026316	0.000000	0.030303	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.095238	0.000000	0.000000	0.000000	0.000000
T7_2	0.000000	0.000000	0.000000	0.030303	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.074074
T7_3	0.000000	0.000000	0.000000	0.030303	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.111111
T8_4	0.000000	0.026316	0.055556	0.060606	0.000000	0.000000	0.066667	0.041667	0.066667	0.066667	0.095238	0.043478	0.083333	0.111111	0.000000
T8_5	0.074074	0.052632	0.055556	0.000000	0.047619	0.066667	0.066667	0.083333	0.066667	0.133333	0.000000	0.000000	0.000000	0.000000	0.037037
T9_4	0.000000	0.026316	0.000000	0.030303	0.000000	0.000000	0.000000	0.041667	0.000000	0.000000	0.047619	0.000000	0.083333	0.111111	0.074074
T9_5	0.000000	0.026316	0.000000	0.000000	0.000000	0.000000	0.066667	0.083333	0.000000	0.000000	0.047619	0.000000	0.083333	0.111111	0.074074
T10_1	0.000000	0.052632	0.055556	0.000000	0.000000	0.066667	0.000000	0.041667	0.066667	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000
T10_7	0.074074	0.078947	0.000000	0.000000	0.047619	0.066667	0.066667	0.041667	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T11_1	0.037037	0.052632	0.000000	0.000000	0.047619	0.000000	0.000000	0.000000	0.066667	0.000000	0.000000	0.000000	0.000000	0.055556	0.000000
T11_2	0.037037	0.026316	0.000000	0.000000	0.047619	0.000000	0.066667	0.041667	0.000000	0.066667	0.000000	0.000000	0.083333	0.111111	0.074074
T12_1	0.037037	0.026316	0.055556	0.060606	0.000000	0.000000	0.000000	0.041667	0.066667	0.000000	0.095238	0.043478	0.166667	0.111111	0.111111
T12_5	0.000000	0.026316	0.000000	0.030303	0.000000	0.000000	0.000000	0.041667	0.066667	0.000000	0.047619	0.043478	0.083333	0.111111	0.074074
T13_1	0.111111	0.078947	0.055556	0.090909	0.000000	0.133333	0.000000	0.041667	0.000000	0.066667	0.095238	0.130435	0.000000	0.000000	0.000000
T13_2	0.000000	0.000000	0.000000	0.030303	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.166667	0.166667	0.111111
T14_1	0.000000	0.000000	0.000000	0.060606	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.095238	0.130435	0.000000	0.000000	0.000000
T14_4	0.000000	0.000000	0.055556	0.090909	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.047619	0.086957	0.000000	0.000000	0.074074
T15_2	0.000000	0.026316	0.000000	0.060606	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.047619	0.130435	0.000000	0.000000	0.000000
T15_5	0.000000	0.000000	0.055556	0.060606	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.047619	0.086957	0.000000	0.000000	0.000000
T16_4	0.037037	0.000000	0.055556	0.030303	0.000000	0.000000	0.000000	0.000000	0.133333	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000
T16_6	0.111111	0.052632	0.111111	0.060606	0.047619	0.133333	0.066667	0.041667	0.133333	0.200000	0.095238	0.043478	0.000000	0.000000	0.000000
T17_11	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T17_13	0.000000	0.052632	0.000000	0.060606	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.166667	0.055556	0.000000

	T8_5	T9_4	T9_5	T10_1	T10_7	T11_1	T11_2	T12_1	T12_5	T13_1	T13_2	T14_1	T14_4	T15_2	T15_5
T1_3	0.035714	0.000000	0.000000	0.103448	0.045455	0.100000	0.047619	0.000000	0.000000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000
T1_5	0.035714	0.000000	0.000000	0.068966	0.045455	0.100000	0.047619	0.000000	0.000000	0.031250	0.000000	0.000000	0.000000	0.045455	0.034483
T2_2	0.035714	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.066667	0.000000	0.000000	0.064516	0.000000	0.000000	0.000000	0.000000
T2_4	0.000000	0.076923	0.117647	0.000000	0.000000	0.000000	0.000000	0.033333	0.050000	0.062500	0.000000	0.095238	0.214286	0.136364	0.068966
T3_4	0.035714	0.000000	0.000000	0.034483	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T3_8	0.035714	0.000000	0.000000	0.068966	0.000000	0.000000	0.000000	0.000000	0.000000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000
T4_1	0.071429	0.000000	0.000000	0.068966	0.045455	0.000000	0.047619	0.033333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T4_4	0.107143	0.076923	0.058824	0.068966	0.045455	0.050000	0.047619	0.000000	0.050000	0.031250	0.032258	0.000000	0.071429	0.045455	0.000000
T5_4	0.071429	0.000000	0.000000	0.103448	0.045455	0.000000	0.000000	0.000000	0.000000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000
T5_5	0.071429	0.000000	0.000000	0.034483	0.045455	0.050000	0.047619	0.000000	0.050000	0.062500	0.000000	0.000000	0.000000	0.000000	0.000000
T6_5	0.000000	0.038462	0.000000	0.000000	0.000000	0.000000	0.000000	0.033333	0.050000	0.062500	0.032258	0.142857	0.142857	0.045455	0.068966
T6_6	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.062500	0.000000	0.000000	0.000000	0.090909	0.068966
T7_2	0.035714	0.115385	0.117647	0.068966	0.000000	0.050000	0.047619	0.000000	0.000000	0.031250	0.096774	0.000000	0.000000	0.000000	0.000000
T7_3	0.000000	0.115385	0.117647	0.000000	0.000000	0.050000	0.095238	0.100000	0.150000	0.000000	0.096774	0.000000	0.000000	0.045455	0.000000
T8_4	0.071429	0.076923	0.117647	0.034483	0.000000	0.100000	0.095238	0.100000	0.100000	0.031250	0.064516	0.095238	0.071429	0.045455	0.068966
T8_5	0.000000	0.038462	0.058824	0.068966	0.045455	0.050000	0.047619	0.033333	0.050000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000
T9_4	0.035714	0.000000	0.117647	0.034483	0.000000	0.050000	0.047619	0.066667	0.050000	0.062500	0.096774	0.047619	0.000000	0.045455	0.068966
T9_5	0.035714	0.076923	0.000000	0.034483	0.000000	0.100000	0.095238	0.066667	0.100000	0.031250	0.064516	0.047619	0.000000	0.045455	0.034483
T10_1	0.000000	0.000000	0.000000	0.000000	0.045455	0.050000	0.047619	0.000000	0.000000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000
T10_7	0.035714	0.000000	0.000000	0.034483	0.000000	0.050000	0.000000	0.000000	0.000000	0.062500	0.000000	0.000000	0.000000	0.000000	0.000000
T11_1	0.035714	0.038462	0.000000	0.000000	0.136364	0.000000	0.095238	0.000000	0.000000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000
T11_2	0.000000	0.076923	0.000000	0.034483	0.045455	0.050000	0.000000	0.066667	0.000000	0.000000	0.096774	0.000000	0.000000	0.000000	0.000000
T12_1	0.035714	0.076923	0.058824	0.034483	0.000000	0.050000	0.095238	0.000000	0.100000	0.062500	0.096774	0.142857	0.071429	0.090909	0.103448
T12_5	0.035714	0.038462	0.000000	0.034483	0.000000	0.000000	0.000000	0.100000	0.000000	0.031250	0.064516	0.095238	0.000000	0.045455	0.103448
T13_1	0.035714	0.000000	0.058824	0.034483	0.090909	0.050000	0.047619	0.000000	0.000000	0.000000	0.096774	0.000000	0.000000	0.045455	0.034483
T13_2	0.000000	0.076923	0.058824	0.000000	0.000000	0.000000	0.047619	0.066667	0.050000	0.031250	0.000000	0.095238	0.000000	0.000000	0.034483
T14_1	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.066667	0.100000	0.000000	0.000000	0.000000	0.000000	0.000000	0.068966
T14_4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.068966
T15_2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.062500	0.032258	0.047619	0.000000	0.000000	0.103448
T15_5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.033333	0.050000	0.031250	0.000000	0.047619	0.214286	0.136364	0.000000
T16_4	0.071429	0.000000	0.000000	0.000000	0.136364	0.050000	0.000000	0.000000	0.000000	0.000000	0.000000	0.047619	0.071429	0.045455	0.000000
T16_6	0.035714	0.038462	0.117647	0.034483	0.136364	0.000000	0.000000	0.066667	0.050000	0.062500	0.064516	0.095238	0.142857	0.090909	0.068966
T17_11	0.000000	0.000000	0.000000	0.000000	0.045455	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T17_13	0.035714	0.038462	0.000000	0.000000	0.045455	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

ANP results: Influence on all other SDG targets: Limit supermatrix

	T1_3	T1_5	T2_2	T2_4	T3_4	T3_8	T4_1	T4_4	T5_4	T5_5	T6_5	T6_6	T7_2	T7_3	T8_4	T8_5	T9_4
T1_3	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000
T1_5	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357
T2_2	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783
T2_4	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822
T3_4	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818
T3_8	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571
T4_1	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938
T4_4	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869
T5_4	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510
T5_5	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932
T6_5	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843
T6_6	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726
T7_2	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324
T7_3	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740
T8_4	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716
T8_5	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566
T9_4	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456
T9_5	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887
T10_1	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226
T10_7	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785
T11_1	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195
T11_2	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496
T12_1	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336
T12_5	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292
T13_1	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779
T13_2	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138
T14_1	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927
T14_4	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274
T15_2	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882
T15_5	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570
T16_4	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316
T16_6	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946
T17_11	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246
T17_13	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736

	T9_5	T10_1	T10_7	T11_1	T11_2	T12_1	T12_5	T13_1	T13_2	T14_1	T14_4	T15_2	T15_5	T16_4	T16_6	T17_11	T17_13
T1_3	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000	0.034000
T1_5	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357	0.034357
T2_2	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783	0.016783
T2_4	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822	0.029822
T3_4	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818	0.005818
T3_8	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571	0.009571
T4_1	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938	0.025938
T4_4	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869	0.042869
T5_4	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510	0.028510
T5_5	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932	0.041932
T6_5	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843	0.026843
T6_6	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726	0.008726
T7_2	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324	0.028324
T7_3	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740	0.037740
T8_4	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716	0.060716
T8_5	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566	0.045566
T9_4	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456	0.040456
T9_5	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887	0.042887
T10_1	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226	0.014226
T10_7	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785	0.017785
T11_1	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195	0.017195
T11_2	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496	0.032496
T12_1	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336	0.060336
T12_5	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292	0.043292
T13_1	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779	0.036779
T13_2	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138	0.035138
T14_1	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927	0.014927
T14_4	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274	0.015274
T15_2	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882	0.010882
T15_5	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570	0.015570
T16_4	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316	0.031316
T16_6	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946	0.067946
T17_11	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246	0.009246
T17_13	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736	0.016736

ANP results: Influence received from all other SDG targets: unweighted supermatrix = weighted supermatrix

	T1_3	T1_5	T2_2	T2_4	T3_4	T3_8	T4_1	T4_4	T5_4	T5_5	T6_5	T6_6	T7_2	T7_3	T8_4	T8_5	T9_4	T9_5	T10_1	T10_7	T11_1	T11_2	T12_1	T12_5	T13_1	T13_2	T14_1	T14_4	T15_2	T15_5	T16_4	T16_6	T17_11	T17_13
T1_3	0.000000	0.076923	0.000000	0.000000	0.000000	0.181818	0.058824	0.066667	0.120000	0.096774	0.000000	0.000000	0.000000	0.000000	0.000000	0.068966	0.000000	0.000000	0.000000	0.133333	0.071429	0.047619	0.022727	0.000000	0.093750	0.000000	0.000000	0.000000	0.000000	0.000000	0.052632	0.058824	0.000000	0.000000
T1_5	0.040000	0.000000	0.153846	0.000000	0.250000	0.181818	0.117647	0.066667	0.040000	0.032258	0.083333	0.100000	0.000000	0.000000	0.024390	0.068966	0.035714	0.034483	0.181818	0.200000	0.142857	0.047619	0.022727	0.033333	0.093750	0.000000	0.000000	0.000000	0.071429	0.000000	0.000000	0.039216	0.000000	0.181818
T2_2	0.040000	0.038462	0.000000	0.000000	0.000000	0.090909	0.000000	0.000000	0.120000	0.064516	0.000000	0.000000	0.000000	0.000000	0.024390	0.034483	0.000000	0.000000	0.090909	0.000000	0.000000	0.000000	0.022727	0.000000	0.031250	0.000000	0.000000	0.076923	0.000000	0.062500	0.052632	0.039216	0.000000	0.000000
T2_4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.033333	0.040000	0.064516	0.083333	0.100000	0.052632	0.045455	0.048780	0.000000	0.035714	0.000000	0.000000	0.000000	0.000000	0.000000	0.045455	0.033333	0.093750	0.050000	0.153846	0.230769	0.142857	0.125000	0.052632	0.039216	0.000000	0.181818
T3_4	0.080000	0.038462	0.230769	0.041667	0.000000	0.181818	0.058824	0.033333	0.080000	0.096774	0.000000	0.000000	0.000000	0.000000	0.000000	0.034483	0.000000	0.000000	0.000000	0.066667	0.071429	0.047619	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.019608	0.000000	0.000000
T3_8	0.040000	0.038462	0.000000	0.000000	0.000000	0.000000	0.058824	0.033333	0.080000	0.064516	0.000000	0.000000	0.000000	0.000000	0.000000	0.034483	0.000000	0.000000	0.090909	0.066667	0.000000	0.000000	0.000000	0.000000	0.062500	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.039216	0.000000	0.000000
T4_1	0.040000	0.038462	0.076923	0.000000	0.000000	0.000000	0.000000	0.033333	0.080000	0.096774	0.000000	0.000000	0.000000	0.000000	0.024390	0.034483	0.000000	0.034483	0.000000	0.066667	0.000000	0.047619	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.019608	0.000000	0.000000
T4_4	0.080000	0.076923	0.000000	0.000000	0.000000	0.000000	0.176471	0.000000	0.120000	0.032258	0.000000	0.000000	0.000000	0.000000	0.024390	0.068966	0.035714	0.068966	0.090909	0.066667	0.000000	0.047619	0.022727	0.033333	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.019608	0.000000	0.000000
T5_4	0.080000	0.038462	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.064516	0.000000	0.000000	0.000000	0.000000	0.024390	0.034483	0.000000	0.000000	0.090909	0.000000	0.071429	0.000000	0.022727	0.033333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.105263	0.039216	0.000000	0.000000
T5_5	0.040000	0.038462	0.000000	0.000000	0.250000	0.000000	0.000000	0.033333	0.040000	0.000000	0.000000	0.000000	0.000000	0.000000	0.024390	0.068966	0.000000	0.000000	0.090909	0.000000	0.000000	0.047619	0.000000	0.000000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000	0.052632	0.058824	0.000000	0.000000
T6_5	0.000000	0.000000	0.000000	0.083333	0.000000	0.000000	0.000000	0.000000	0.000000	0.032258	0.000000	0.200000	0.000000	0.000000	0.048780	0.000000	0.035714	0.034483	0.000000	0.000000	0.000000	0.000000	0.045455	0.033333	0.062500	0.000000	0.153846	0.076923	0.071429	0.062500	0.000000	0.039216	0.000000	0.000000
T6_6	0.000000	0.038462	0.000000	0.083333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.125000	0.000000	0.000000	0.000000	0.024390	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.022727	0.033333	0.093750	0.000000	0.230769	0.153846	0.214286	0.125000	0.000000	0.019608	0.000000	0.000000
T7_2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.024390	0.000000	0.035714	0.034483	0.000000	0.000000	0.000000	0.047619	0.045455	0.033333	0.000000	0.100000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.181818
T7_3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.048780	0.000000	0.071429	0.068966	0.000000	0.000000	0.071429	0.095238	0.045455	0.066667	0.000000	0.150000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.090909
T8_4	0.000000	0.000000	0.153846	0.041667	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.041667	0.000000	0.105263	0.136364	0.000000	0.034483	0.071429	0.068966	0.000000	0.000000	0.000000	0.095238	0.068182	0.066667	0.000000	0.150000	0.000000	0.153846	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T8_5	0.040000	0.038462	0.076923	0.000000	0.250000	0.090909	0.117647	0.100000	0.080000	0.064516	0.000000	0.000000	0.052632	0.000000	0.048780	0.000000	0.035714	0.034483	0.000000	0.066667	0.071429	0.000000	0.022727	0.033333	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000	0.105263	0.019608	0.000000	0.090909
T9_4	0.000000	0.000000	0.000000	0.083333	0.000000	0.000000	0.000000	0.066667	0.000000	0.000000	0.041667	0.000000	0.157895	0.136364	0.048780	0.034483	0.000000	0.068966	0.000000	0.000000	0.071429	0.095238	0.045455	0.033333	0.000000	0.100000	0.000000	0.000000	0.000000	0.000000	0.000000	0.019608	0.000000	0.090909
T9_5	0.000000	0.000000	0.000000	0.083333	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.000000	0.000000	0.105263	0.090909	0.048780	0.034483	0.071429	0.000000	0.000000	0.000000	0.000000	0.000000	0.022727	0.000000	0.031250	0.050000	0.000000	0.000000	0.000000	0.000000	0.000000	0.039216	0.000000	0.000000
T10_1	0.120000	0.076923	0.000000	0.000000	0.250000	0.181818	0.117647	0.066667	0.120000	0.032258	0.000000	0.000000	0.105263	0.000000	0.024390	0.068966	0.035714	0.034483	0.000000	0.066667	0.000000	0.047619	0.022727	0.033333	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.019608	0.000000	0.000000
T10_7	0.040000	0.038462	0.000000	0.000000	0.000000	0.000000	0.058824	0.033333	0.040000	0.032258	0.000000	0.000000	0.000000	0.000000	0.000000	0.034483	0.000000	0.000000	0.090909	0.000000	0.214286	0.047619	0.000000	0.000000	0.062500	0.000000	0.000000	0.000000	0.000000	0.000000	0.157895	0.058824	0.200000	0.090909
T11_1	0.080000	0.076923	0.000000	0.000000	0.000000	0.000000	0.000000	0.033333	0.000000	0.032258	0.000000	0.000000	0.052632	0.045455	0.048780	0.034483	0.035714	0.068966	0.090909	0.066667	0.000000	0.047619	0.022727	0.000000	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000	0.052632	0.000000	0.000000	0.000000
T11_2	0.040000	0.038462	0.000000	0.000000	0.000000	0.000000	0.058824	0.033333	0.000000	0.032258	0.000000	0.000000	0.052632	0.090909	0.048780	0.034483	0.035714	0.068966	0.090909	0.000000	0.142857	0.000000	0.045455	0.000000	0.031250	0.050000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
T12_1	0.000000	0.000000	0.153846	0.041667	0.000000	0.000000	0.058824	0.000000	0.000000	0.000000	0.041667	0.000000	0.000000	0.136364	0.073171	0.034483	0.071429	0.068966	0.000000	0.000000	0.000000	0.095238	0.000000	0.100000	0.000000	0.100000	0.153846	0.153846	0.000000	0.062500	0.000000	0.039216	0.000000	0.000000
T12_5	0.000000	0.000000	0.000000	0.041667	0.000000	0.000000	0.000000	0.033333	0.000000	0.032258	0.041667	0.000000	0.000000	0.136364	0.048780	0.034483	0.035714	0.068966	0.000000	0.000000	0.000000	0.000000	0.045455	0.000000	0.000000	0.050000	0.153846	0.000000	0.000000	0.062500	0.000000	0.019608	0.000000	0.000000
T13_1	0.040000	0.038462	0.000000	0.083333	0.000000	0.090909	0.000000	0.033333	0.040000	0.064516	0.083333	0.200000	0.052632	0.000000	0.024390	0.034483	0.071429	0.034483	0.090909	0.133333	0.071429	0.000000	0.045455	0.033333	0.000000	0.050000	0.000000	0.000000	0.142857	0.062500	0.000000	0.039216	0.000000	0.000000
T13_2	0.000000	0.000000	0.153846	0.000000	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.041667	0.000000	0.157895	0.136364	0.048780	0.000000	0.107143	0.068966	0.000000	0.000000	0.000000	0.142857	0.068182	0.066667	0.093750	0.000000	0.000000	0.000000	0.071429	0.000000	0.000000	0.039216	0.000000	0.000000
T14_1	0.000000	0.000000	0.000000	0.083333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.125000	0.000000	0.000000	0.000000	0.048780	0.000000	0.035714	0.034483	0.000000	0.000000	0.000000	0.000000	0.068182	0.066667	0.000000	0.100000	0.000000	0.000000	0.071429	0.062500	0.052632	0.039216	0.000000	0.000000
T14_4	0.000000	0.000000	0.000000	0.125000	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.083333	0.000000	0.000000	0.000000	0.024390	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.022727	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.187500	0.052632	0.039216	0.000000	0.000000
T15_2	0.000000	0.038462	0.000000	0.125000	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.041667	0.200000	0.000000	0.045455	0.024390	0.000000	0.035714	0.034483	0.000000	0.000000	0.000000	0.000000	0.045455	0.033333	0.031250	0.000000	0.000000	0.000000	0.000000	0.187500	0.052632	0.039216	0.000000	0.000000
T15_5	0.000000	0.038462	0.000000	0.083333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.083333	0.200000	0.000000	0.000000	0.048780	0.000000	0.071429	0.034483	0.000000	0.000000	0.000000	0.000000	0.068182	0.100000	0.031250	0.050000	0.153846	0.153846	0.214286	0.000000	0.000000	0.039216	0.000000	0.000000
T16_4	0.040000	0.038462	0.000000	0.000000	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.000000	0.000000	0.052632	0.000000	0.000000	0.034483	0.000000	0.000000	0.000000	0.066667	0.000000	0.000000	0.000000	0.033333	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.058824	0.200000	0.000000
T16_6	0.040000	0.038462	0.000000	0.000000	0.000000	0.000000	0.117647	0.033333	0.000000	0.064516	0.041667	0.000000	0.000000	0.000000	0.024390	0.034483	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.022727	0.033333	0.031250	0.000000	0.000000	0.000000	0.000000	0.000000	0.157895	0.000000	0.200000	0.000000
T17_11	0.040000	0.038462	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.034483	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.090909
T17_13	0.080000	0.076923	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.041667	0.000000	0.052632	0.000000	0.024390	0.068966	0.035714	0.034483	0.000000	0.000000	0.000000	0.000000	0.045455	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.052632	0.058824	0.400000	0.000000

ANP results: Influence received from all other SDG targets: Limit supermatrix

	T1_3	T1_5	T2_2	T2_4	T3_4	T3_8	T4_1	T4_4	T5_4	T5_5	T6_5	T6_6	T7_2	T7_3	T8_4	T8_5	T9_4	T9_5	T10_1	T10_7	T11_1	T11_2	T12_1	T12_5	T13_1	T13_2	T14_1	T14_4	T15_2	T15_5	T16_4	T16_6	T17_11	T17_13
T1_3	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240	0.033240
T1_5	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546	0.065546
T2_2	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540	0.023540
T2_4	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379	0.049379
T3_4	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803	0.028803
T3_8	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732	0.019732
T4_1	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756	0.016756
T4_4	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821	0.029821
T5_4	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029	0.018029
T5_5	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441	0.024441
T6_5	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224	0.034224
T6_6	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714	0.041714
T7_2	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747	0.014747
T7_3	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780	0.020780
T8_4	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216	0.032216
T8_5	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492	0.037492
T9_4	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552	0.029552
T9_5	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408	0.018408
T10_1	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204	0.040204
T10_7	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033	0.029033
T11_1	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388	0.026388
T11_2	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900	0.026900
T12_1	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234	0.037234
T12_5	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927	0.023927
T13_1	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345	0.052345
T13_2	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470	0.033470
T14_1	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053	0.026053
T14_4	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721	0.021721
T15_2	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073	0.037073
T15_5	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410	0.046410
T16_4	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182	0.012182
T16_6	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545	0.018545
T17_11	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223	0.007223
T17_13	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874	0.022874

8.3.1.2 Re-calculation of SDG target rankings of Weitz et al. (2018) case study

Re-calculation of SDG target rankings of Weitz et al. (2018) case study only considering positive interaction scores

	Synergistic potential (2nd order)		Progress controllability (1st order)	
Rank	SDG target	influence	SDG target	influence
1	16.6	567	1.5	38
2	12.1	508,5	2.4	33
3	8.4	504,5	13.1	32
4	12.5	376,5	13.2	31
5	9.5	364,5	12.1	30
6	4.4	364	10.1	29
7	5.5	362,5	15.5	29
8	8.5	351	8.5	28
9	9.4	349,5	1.3	27
10	13.1	348	8.4	27
11	7.3	323,5	9.4	26
12	6.5	274,5	4.4	24
13	13.2	272	6.6	23
14	5.4	265	10.7	22
15	2.4	263,5	15.2	22
16	11.2	263,5	3.4	21
17	1.5	261,5	6.5	21
18	1.3	249,5	11.2	21
19	16.4	248	14.1	21
20	4.1	238,5	17.13	21
21	7.2	225,5	11.1	20
22	10.7	174	12.5	20
23	14.4	173	2.2	18
24	2.2	164	7.3	18
25	11.1	161,5	9.5	17
26	14.1	159,5	16.6	17
27	15.5	159,5	3.8	15
28	15.2	137,5	4.1	15
29	10.1	130	5.4	15
30	17.13	113,5	5.5	15
31	3.8	112	14.4	14
32	6.6	111,5	7.2	12
33	3.4	52,5	16.4	11
34	17.11	44,5	17.11	4