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A portfolio decision analysis approach for selecting a subset of interdependent actions: The case of a regional climate roadmap in Finland

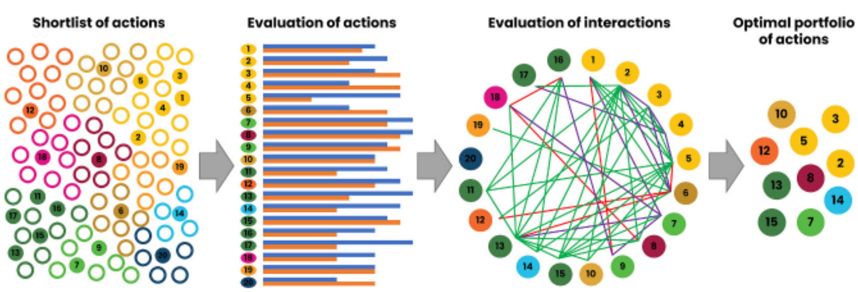
Jyri Mustajoki [a,*], Juuso Liesiö [b], Miika Kajanus [c], Tuomo Eskelinen [c], Saara Karkulahti [d], Taeyoung Kee [b], Anni Kesänen [c], Tapio Kettunen [d], Jyri Wuorisalo [c], Mika Marttunen [a]

[a] Finnish Environment Institute, Helsinki, Finland
[b] Aalto University, Espoo, Finland
[c] Savonia University of Applied Sciences, Kuopio, Finland
[d] Centre for Economic Development, Transport and the Environment of North Savo, Kuopio, Finland

HIGHLIGHTS

- A new portfolio approach is presented for considering interactions between actions.
- A shortlist of actions and holistic evaluation of interactions to reduce workload
- Sensitivity analysis on the intensity of the interactions suggested
- Helped to understand synergies/trade-offs between actions in a climate roadmap case

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we present a structured approach based on portfolio decision analysis to support the consideration of interdependencies between actions (i.e. interactions) in the selection of an efficient portfolio. One of the main challenges in modelling interactions is that the possible number of them between the pairs of actions increases exponentially with the number of actions. In environmental management, the problems can include tens of possible actions potentially leading to hundreds of pairwise interactions between them. For example, a strategy for mitigating climate change can consist of various actions in different sectors for improving technology, reducing emissions and the sequestration of carbon. Our approach aims to reduce the burden of assessing interactions by initially selecting a shortlist of actions based on specific heuristics and focusing on modelling interactions exclusively within this chosen set of actions. Another feature of the approach is the use of holistic evaluation of interactions to further reduce the cognitive load of stakeholders making the assessment. As a possible disadvantage, these features may increase the imprecision related to the results of the model. To analyse the impacts of this imprecision, we propose a way to carry out sensitivity analysis on the basis of how intensively the interactions would be taken into account in the modelling. The applicability of the approach was tested in a case related to the roadmap to a carbon neutral North Savo region in Finland by the year 2035. The approach helped to better understand synergies and trade-offs when putting the actions of the roadmap into practice, which is expected to lead to better results in terms of preparedness and adaptation to climate change.

* Corresponding author at: Finnish Environment Institute, Latokartanonkaari 11, 00790 Helsinki, Finland.
E-mail address: jyri.mustajoki@syke.fi (J. Mustajoki).

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1. Introduction

The green transition towards a carbon neutral society is at the core of the European Green Deal (EU, 2019), and also an integral part of the United Nations' 2030 Agenda and its Sustainable Development Goal (SDG) framework (United Nations, 2015). Both programmes emphasise the need for systemic approaches to deal with the complexity of the problem (including the interactions between different parts of the system), and to find solutions that are sustainable in terms of environmental, social and economic impacts (Purvis et al., 2019).

Various multi-criteria methods have been developed to support systematic analysis and the comparison of alternatives, considering the diverse dimensions of sustainability (see e.g., Huang et al., 2011; Cegan et al., 2017). One such method is portfolio decision analysis (PDA) (see, e.g., Salo et al., 2011; Lahtinen et al., 2017; Liesiö et al., 2021), which provides structured support for identifying an efficient set of actions within the given resource constraints and in terms of multiple criteria. The application potential of PDA in environmental decision-making is high, as many problems are typically portfolio problems (Lahtinen et al., 2017; Cohen et al., 2019), but in spite of this, relatively few real-world cases have so far been carried out (e.g., Convertino and Valverde Jr, 2013; Fasth et al., 2020; Krainyk et al., 2021; Marttunen et al., 2023). This is partly because the opportunities of the method have not yet been widely recognised (Lahtinen et al., 2017), and also because of the challenges associated with the complexity of PDA models (Liesiö et al., 2021). One of the main challenges is the modelling of interdependencies between the actions (a.k.a. interactions) and their consequences (e.g., synergies or antagonist effects), which can be a very laborious task in cases involving tens of possible actions, and consequently potentially hundreds of interactions between them (Durbach et al., 2020). A critical concern in the development of approaches to support the application of PDA is finding a balance between the different needs of the modelling, such as model realism vs. data requirements, or time constraints vs. the in-depth quality of the assessment (e.g., Sarkki et al., 2014).

This paper presents a structured approach aimed at supporting the application of PDA in environmental management, particularly in situations where there are numerous potential actions with interactions between them. In the approach, we first identify a compact set of the most efficient single actions in terms of multiple criteria (e.g., only 10–20 actions), and then carry out the assessment of joint effects only within this set with the aim of reducing the cognitive load of carrying out the assessment. As another means to ease the cognitive load, we propose holistic evaluation of all the interactions related to each action jointly instead of individually evaluating interactions between all the possible pairs of actions. As a result, the analysis yields an efficient set of actions when taking the most relevant pairwise interactions into account. To analyse the impacts of the possible imprecision due to the proposed means, we also suggest a way to analyse the sensitivity of the results to the intensity of taking the joint effects into account.

We tested the use of the approach in a case related to the roadmap to a carbon neutral North Savo region in Finland by 2035, which defines the goals, objectives and main actions for regional climate work. The roadmap includes one hundred and one actions covering five focus areas cross-cutting six economic sectors. Although the actions were identified and selected by a wide range of participants, they are still strongly based on sectoral expertise, thus lacking analysis of how the actions are interrelated. As far as we know, our case represents the first attempt to analyse the interactions among the actions outlined in a regional climate roadmap.

This paper is structured as follows. Section 2 describes the methods applied in our proposed approach, as well as the method utilised in its development. Section 3 describes the approach itself and Section 4 its application in the North Savo case. The applicability of the approach in practice is discussed in Section 5, and Section 6 concludes the paper.

2. Methods

In this section, we describe both the methods that we applied in our approach and a case study (PDA and SDG), as well as the methods we employed in the development of the approach (case study and action research approaches).

2.1. Portfolio decision analysis and interactions in PDA

PDA refers to the theory, methods and practices developed to help with decision problems in selecting a portfolio of actions (e.g., projects, investments, initiatives) (Salo et al., 2011). Such decisions are often complicated by the presence of multiple criteria and several resource constraints (Kleinmuntz, 2007; Montibeller et al., 2009; Lopes and de Almeida, 2015). PDA methods often rely on decision analysis approaches to capture decision makers' preferences and utilize mathematical optimisation in identifying the most preferred portfolio of actions.

Perhaps the most common multi-criteria PDA approach is to use the additive preference model (Golabi et al., 1981; Parnell et al., 2002; Kleinmuntz, 2007; Gurgur and Morley, 2008; Mild et al., 2015). In this model, portfolio value is represented by the sum of multi-criteria values of the actions included in the portfolio. The popularity of the additive preference model can be attributed to three factors. First, it does not require any preference elicitation other than specification of the multi-criteria value function used to evaluate individual actions. Second, it is possible to obtain the optimal action portfolio using standard integer linear programming (ILP) algorithms. Lastly, additive preference models are well grounded in terms of decision theory due to their strong axiomatic foundations (Liesiö, 2014; Liesiö and Punkka, 2014; Morton, 2015; Liesiö and Vilkkumaa, 2021).

A critical concern with the additive preference model is that it does not allow modelling of the joint effects of implementing multiple actions simultaneously (i.e., synergies or antagonistic effects). In the additive preference model, adding one action to the portfolio always increases the portfolio value by a constant amount, regardless of what actions the portfolio contains. This absence of a mechanism to capture project interactions has motivated the development of two approaches. The first approach is to introduce non-linearity to the portfolio value function so that the function can represent interaction effects associated with different subsets of projects (Almeida and Duarte, 2011; Gutjahr and Froeschl, 2013; Schilling and Werners, 2016; Liesiö and Vilkkumaa, 2021). The second approach is to add a dummy action to the model for each interaction (Liesiö et al., 2008; Carazo et al., 2010), as well as additional constraints that ensure that a dummy action can be included in the portfolio if and only if the actions triggering the interaction are also included.

Earlier research has mostly focused on computational aspects of the modelling of interactions without much consideration of the process needed for identifying and quantifying interactions. Such a process requires many steps, starting from collecting and aggregating expert judgements, evaluating the accuracy or reliability of these estimates and, finally, using the estimates in a portfolio decision analysis model. However, the estimation of interaction effects can also be very challenging in practice. There can be dozens of action candidates, and at worst, the assessment of their joint effects would require going through the interactions between all of the possible combinations of actions. In cases with certain patterns of interactions, these can be modelled, for example, with multiplicative or some other heuristics (e.g., Grushka-Cockayne et al., 2008; Durbach et al., 2020) or by approximating the interactions somehow (e.g., Toppila et al., 2011). Nevertheless, there is often a need to make a trade-off between the accuracy of the analysis and the workload required for the assessment.

In this paper, we develop a practical approach for capturing interactions in portfolio decision analysis applications. This approach is based on a portfolio model that augments the additive portfolio value function with additional terms capturing interaction effects between pairs of actions. Moreover, we design an assessment process that utilises holistic assessment of interactions that avoids the need to evaluate interactions between each pair of actions separately.

2.2. Sustainable Development Goal framework

The SDG framework provides an integrated framework for balancing the economic, social and environmental dimensions of sustainable development (Griggs et al., 2013). It was adopted by the United Nations General Assembly within the universal 2030 Agenda for Sustainable Development (United Nations, 2015). The framework includes 17 distinct goals (e.g., "3. Good health and well-being"). Under these, there are 169 individual targets (e.g., "3.1. By 2030, reduce the global maternal mortality ratio to less than 70 per 100,000 live births"), which were initially designed to act as aspirational objectives in giving guidelines to national governments for their planning processes, policies and strategies (United Nations, 2019).

Besides providing a generic framework for the assessment, the SDG framework can be utilised in various ways to support environmental assessments. For example, it provides a unified set of 231 global indicators for monitoring the performance of different countries against the targets, which can be used, for example, to analyse the progress of the countries towards achieving the goals (e.g., Schmidt-Traub et al., 2017; Mustajoki et al., 2022). The SDG framework can also be applied to identify and enhance comprehension of the intricate relationships between the goals and targets, thereby highlighting the challenges and synergies in achieving the goals. Many approaches have been developed to illustrate the interlinkages between the goals with matrices based, for example, on expert evaluation (e.g. Nilsson et al., 2016, 2017; Weitz et al., 2018; Van Soest et al., 2019; Pham-Truffert et al., 2020), statistical data analysis (e.g. Kroll et al., 2019; Ronzon and Sanjuán, 2020) or on data collected from multiple sources (e.g. Miola et al., 2019). Many of these analyses also provide interactive tools for analysing the interlinkages between the targets (e.g., CDEdatablog tool,[1] NDC-SDG Connections tool,[2] SDG Interlinkages Analysis & Visualisation Tool (V4.0),[3] or JRC Interlinkages tool[4]).

2.3. Case study and action research approaches

In the development of our approach, we applied a process which has features of both case study (CS) and action research (AR) approaches (Montibeller et al., 2009). CS is a research approach that is used to generate an in-depth, multi-faceted understanding of a complex issue in its real-life context (Crowe et al., 2011). It is extensively used in a wide variety of disciplines, particularly in the social sciences (Feagin et al., 1991). AR is a research strategy that permits systematic investigation of an issue while aiming to improve organisational practices. It has been advocated as an appropriate method for studying MCDA interventions, which could support organisational decision-making (Montibeller et al., 2009).

Both approaches relate to real-world problems that typically engage experts, researchers and stakeholder representatives. Therefore, forming parallel groups or repeating the same process is not possible. The approaches aim to find answers to 'how', 'what' and 'why' questions, such as 'how is the intervention being implemented and what are its strengths and weaknesses?' They enable learning and the sharing of experiences so that others can learn from past successes and failures. They also allow reflection and understanding of what worked well and what could have been done differently. In our case, we both observed discussions and used structured questionnaires in workshops to address these concerns when gathering information on participants' opinions and attitudes.

3. Multi-criteria approach for selecting a portfolio of interdependent actions

The approach proposed in this paper focuses on supporting the explicit inclusion of interactions in PDA. The aim is to provide procedural support in carrying out the process of considering interactions, as well as theoretical support in analysing, for example, the sensitivity of the results to the intensity of interactions.

3.1. Description of the approach

In general, the proposed approach follows the steps of the structured decision-making approach (Gregory et al., 2012), while also incorporating key elements of portfolio decision analysis (Salo et al., 2011). The main phases of the process are:

1. Identification and framing of the problem
   a. Identification of the participants
   b. Identification of the criteria
   c. Identification of the actions
2. Analysis of single actions
   a. Estimation of the performances of single actions in terms of each criterion
   b. Eliciting of trade-offs between criteria
   c. Calculation of the overall values of single actions
   d. Selection of the most efficient single actions (circa 10–20 actions) for further analysis
3. Analysis of interactions between the actions
   a. Estimation of the level of synergies and antagonistic effects for each pair of actions as opposed to simply summing the single values of the actions
   b. Calculation of the efficient portfolios of the actions
   c. Sensitivity analysis of different intensities of taking synergies and antagonistic effects into account
4. Policy recommendations
   a. Making recommendations about the actions to be implemented
   b. Implementing the actions and monitoring the implementation

The novelty of the proposed approach lies in the modelling of the interactions between the actions in phases 2d and 3a–c, and in this paper, we focus on these phases. A general description of the other phases can be found, for example, in Gregory et al. (2012), and good examples of applying the process in practice, for example, in Lienert et al. (2015) and Runge et al. (2020).

3.2. Multi-criteria value model for action portfolios

Identification of the action combinations that contribute to the multiple criteria is supported by a tailored portfolio decision analysis model (PDA; for recent reviews, see Lahtinen et al., 2017; Liesiö et al., 2021). In this model, each action x^j, $j \in \{1, \dots, m\}$, is evaluated with regard to criteria $i \in \{1, \dots, n\}$. The overall value of each action x^j is captured by an additive multi-criteria value function

$$v(x^j) = \sum_{i=1}^{n} w_i v_i(x_i^j), \quad (1)$$

where x_i^j is the performance of the jth action with regard to the ith criterion, v_i is the criterion-specific value function for the ith criterion and w_i is the importance weight of the ith criterion. Without loss of generality, the criterion weights $w = (w_1, \dots, w_n)$ can be scaled so that they belong to the set $W^0 = \{(w_1, \dots, w_n) \in \mathbb{R}_+^n \mid \sum_{i=1}^n w_i = 1\}$ and the

[1] https://datablog.cde.unibe.ch/index.php/2019/08/29/sdg-interactions/.
[2] https://sdg.iisd.org/news/online-tool-and-database-analyze-ndc-sdg-links/.
[3] https://sdginterlinkages.iges.jp/visualisationtool.html.
[4] https://knowsdgs.jrc.ec.europa.eu/intro-interlinkages.

criterion-specific value functions so that $v_i(\cdot) \in [0,1]$ for all $i \in \{1, \dots, n\}$.

A portfolio of actions is modelled with binary decision variables $z = (z_1, \dots, z_m)$, where $z_j = 1$ ($z_j = 0$) indicates that the jth action is (not) included in the portfolio. As a starting point, we use the linear-additive portfolio value function (Golabi et al., 1981; Liesiö, 2014) to evaluate the action portfolios. With this function, the value of each portfolio is obtained as the sum of values of those actions ($v(x^j)$) that are included in the portfolio. Formally, the linear value of portfolio z is given by

$$V_L(z) = \sum_{j=1}^{m} z_j v(x^j). \tag{2}$$

This linear-additive portfolio value model cannot incorporate interactions among the actions, as the added value resulting from including an action in a portfolio is constant, regardless of what other actions are included in the portfolio. To address this shortcoming, we extend the value model with an additional term that captures the interaction effects. Formally, we denote by $s(j,j')$, where $j < j'$, the value change in the linear-additive value that results if the portfolio includes both actions j and j'. Thus, the total interaction effect for portfolio z is given by

$$V_I(z) = \sum_{j=1}^{m-1} \sum_{j'=j+1}^{m} z_j z_{j'} s(j,j'). \tag{3}$$

The overall portfolio value, accounting for both the linear additive value resulting from the inclusion of individual actions as well as the interaction effects resulting from the inclusion of specific pairs of actions, is defined as

$$V(z) = V_L(z) + \beta V_I(z), \tag{4}$$

where $\beta \in [0, \infty)$ is the weight for the interaction effects. In essence, parameter β can be used to control the magnitude of the interaction effects V_I compared to the linear-additive portfolio value V_L. For instance, suppose the interaction parameters have been assessed using a scaling in which interaction with the coefficient $s(j,j') = b$ increases the portfolio value by an amount that is equal to the addition of an action with value $v(x) = b$. In this case, the weight $\beta = 1$ corresponds to the assumptions that the interaction magnitudes are correctly assessed, while weights $\beta < 1$ and $\beta > 1$ correspond to under- and over-weighting of the interaction effects compared to the actions' individual values, respectively. Note that applying weight $\beta = 0$ eliminates the interactions V_I from the portfolio value function, and as a result, the portfolio value function V is equivalent to the linear portfolio value function V_L. Moreover, the weight $\beta = \infty$ disregards the individual values of actions (V_L) and thus evaluates portfolios purely based on the interaction effects they produce (V_I).

In practice, assessing the coefficients $s(j,j')$ can be difficult and time-consuming. This is because the number of the coefficients to be assessed grows quickly with the number of projects m. Moreover, these coefficients cannot in general be assessed by considering concrete changes performances of actions (i.e., $x_i^j, x_i^{j'}, i \in \{1, \dots, m\}$) resulting from the interaction, as $s(j,j')$ quantifies the strength of preference for a portfolio containing both actions x^j and $x^{j'}$ compared to portfolios containing only one of these actions. We seek to address these challenges by approximating the coefficients using the formula

$$s(j,j') = \alpha(j,j') v(x^j) v(x^{j'}), \tag{5}$$

where $\alpha(j,j') \in [-1,1]$. This allows us to deploy an assessment process for the interactions in which the experts consider the relative strengths of the interactions $\alpha(j,j') \in [-1,1]$ and the above formula is then used to scale these assessments so that interactions between high-value actions are larger in absolute terms than those between low-value actions.

Given the actions values $v(x^1), \dots, v(x^m)$ and the interaction coefficients $s(j,j'), j \in \{1, \dots m\}, j < j'$ the optimal action portfolio is obtained as the solution to the zero-one linear programming (ZOLP) problem

$$\begin{gathered} max \sum_{j=1}^{m} z_j v(x^j) + \beta \sum_{j=1}^{m-1} \sum_{j'=j+1}^{m} y_{jj'} s(j,j') \\ Az \le B \\ z_j + z_{j'} - 1 \le 2y_{jj'} \le z_j + z_{j'} \forall j \in \{1, \dots, m-1\}, j' \in \{j+1, \dots m\} \\ z_j, y_{j,j'} \in \{0,1\} \forall j \in \{1, \dots, m-1\}, j' \in \{j+1, \dots m\}, \end{gathered} \tag{6}$$

where matrix $A \in \mathbb{R}^{q \times m}$ and vector $B \in \mathbb{R}^q$ encode the q portfolio feasibility constraints, such as limited resources. Note that the second set of constraints ensures that auxiliary binary variables satisfy $y_{jj'} = z_j z_{j'}$ for all $j \in \{1, \dots, m-1\}$ and $j' \in \{j+1, \dots m\}$.

4. Climate roadmap to a carbon neutral North Savo region by 2035

4.1. Development of the roadmap

North Savo is the sixth largest region in Finland, with a total area of 20,366 km^2 and a population of 248,400 inhabitants. The North Savo region includes 19 municipalities, of which five are cities and towns. Climate planning is coordinated by the Centre for Economic Development, Transport and the Environment of North Savo and the Regional Council of Pohjois-Savo (i.e., North Savo). Based on data for 2018, the greenhouse gas emissions of North Savo totalled 2192 kt CO_2-eq. The largest emissions were caused by road traffic (26 %), heating (21 %) and agriculture (20 %) (Benviroc and Luonnonvarakeskus, 2020). The land use sector was a sink of 736 kt CO_2-eq, mainly based on forests, and net emissions were thus 1456 kt CO_2-eq.

To reduce greenhouse gas emissions, a project aimed at creating a roadmap to a carbon neutral North Savo region by 2035 (hereafter the Climate Roadmap) was launched in 2020. The project was carried out in wide cooperation with local actors during autumn 2020 and spring 2021. It included nine workshops, in which 146 persons from over 60 organisations participated.

A scenario created in the project showed that it could be possible to achieve carbon neutrality in North Savo by 2035. The scenario includes actions such as increasing the share of wind energy to 20 % as the primary energy source by constructing 330 wind power plants, a marked increase in public transport, cutting down the utilisation of oil and peat energy, the introduction of a circular economy, a marked change towards carbon neutral agriculture, and the increasing of carbon sinks in forests. Moreover, the need to be prepared for extreme weather and other climate change effects was emphasised. Carbon neutral scenarios constructed as a part of North Savo's regional plan 2040 had similar conclusions. In addition, the smart specialisation strategy for the North Savo region emphasises the climate, circular economy and sustainable development as being among the seven cross-cutting themes.

The roadmap defines the goals, objectives and main actions for regional climate work. Both climate change mitigation and adaptation have been considered in the actions. The main goal is for the North Savo region to become carbon neutral by the year 2035. Greenhouse gas emissions should be reduced by at least 80 % from the level of 2007, and remaining emissions should be sequestrated or compensated sustainably.

The Climate Roadmap includes five main objectives listed in Fig. 1. For each objective, there are measures in six different sectors: "Agriculture and forestry" (Land), "Traffic and logistics" (Traffic), "Energy and water supply" (Energy), "Industry" (Industry), "Food, consumption and waste management" (Food) and "Regional planning, construction and housing" (Housing). In addition, there are cross-sectional "Common measures" for all the objectives.

The implementation of the Climate Roadmap is coordinated by Centre for Economic Development, Transport and the Environment of North Savo. The regional steering group consists of 32 members from 27 organisations. The steering group is also responsible for monitoring the roadmap.

4.2. Applying the proposed approach in the case of the climate roadmap for the North Savo region

As a part of the development of the Climate Roadmap, we tested the approach proposed in Section 3 in selecting the set of efficient actions for the roadmap so that different objectives would be met. An essential part of the work was the linking of the actions to SDGs to ensure coverage of different types of impacts, as well as consideration of the synergies and antagonistic effects between the actions in the analysis. Fig. 2 presents the process of applying the approach in practice in the Climate Roadmap work.

Next, we provide a comprehensive account of the crucial stages within the process as seen through our approach, which encompasses the preliminary assessment of actions, the first workshop, and the conclusive evaluation of actions and their interactions.

4.2.1. Preliminary evaluation of the actions

4.2.1.1. Linking actions to SDGs. In the work carried out for the development of the Climate Roadmap, cross-cutting SDGs for the whole roadmap had already been identified. This provided us a good overview of which SDGs are covered. To make the assessment more explicit, we analysed on the action level which SDG targets are promoted by each action and which SDG target is the most relevant for each action. This information could then be used to ensure that all the main dimensions of sustainability would be covered when considering the most efficient portfolio of actions. In practice, we systematically reviewed all 101 actions as an expert task and determined the overarching SDG associated with each action outlined in the roadmap.

4.2.1.2. Preliminary evaluation of the actions with respect to carbon neutrality and preparedness. The preliminary evaluation of the actions was carried out by a panel of six experts. Each expert evaluated all 101 actions against two specific criteria: 1) the level of significance of the action in terms of achieving *carbon neutrality* and 2) the level of significance of the action in terms of achieving *preparedness* (including adaptation to climate change). A scale from 1 (not significant at all) to 5 (very significant) was applied with both criteria. On each action, the estimate for the significance of the action in relation to achieving *carbon neutrality* was calculated as an average of the corresponding evaluations made by six experts, and similarly for *preparedness*. One should note that these preliminary expert evaluations were only used for selecting the shortlist of actions for further analysis (see next paragraph), but not in the actual evaluations.

4.2.1.3. Selection of the shortlist of actions for further analysis. In the next phase, we created a shortlist of actions for further analysis on the basis of the information obtained from the expert evaluation of actions and the SDG analysis. The SDG analysis was made as an expert assessment, in which each action was linked to the SDG target that was deemed most relevant for that action. An action was included in the shortlist if one or more of the following conditions was met:

- The action was among the top five actions in terms of *carbon neutrality*.
- The action was among the top five actions in terms of *preparedness*.
- The action had the best average of *carbon neutrality* and *preparedness* in its main SDG category (i.e., the SDG goal under which the most relevant SDG target of the action belongs to).
- The action had the best average of *carbon neutrality* and *preparedness* in its sector (Land, Traffic, Energy, Industry, Food and Housing).

Thus, the first two conditions were related to a single criterion (either *carbon neutrality* or *preparedness*), and the latter two to their average. As a result, 21 actions were selected for the shortlist. Finally, the action "Non-combustion-based energy technology is introduced" was abandoned because its meaning was so similar to the action "Development and deployment of non-combustion energy technologies and energy storage". The 20 preselected actions in the shortlist were numbered from 1 to 20, and they are presented in Table 1.

4.2.2. Workshop 1 for evaluating the actions

To obtain stakeholder views of the actions, we organised a three-hour evaluation workshop online in Teams in mid-January 2022. Altogether, 26 experts representing 10 different organisations participated in the workshop. The participants received the following preliminary materials: guidelines, objectives and a programme for the workshop, a presentation of the preselected actions (participants were asked to indicate if any important action was missing), background assumptions to support evaluations, and links to useful materials such as the North

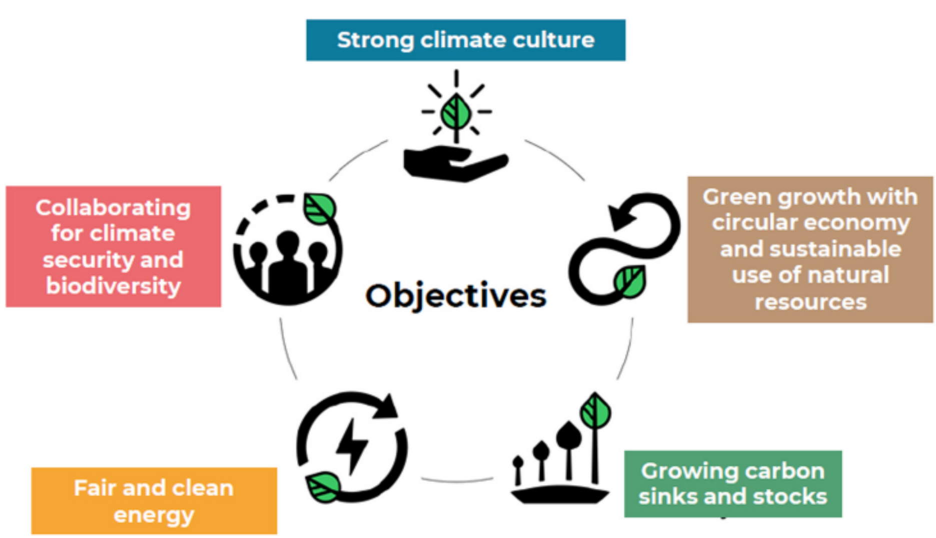

Fig. 1. The main objectives of the Climate Roadmap for the North Savo region.

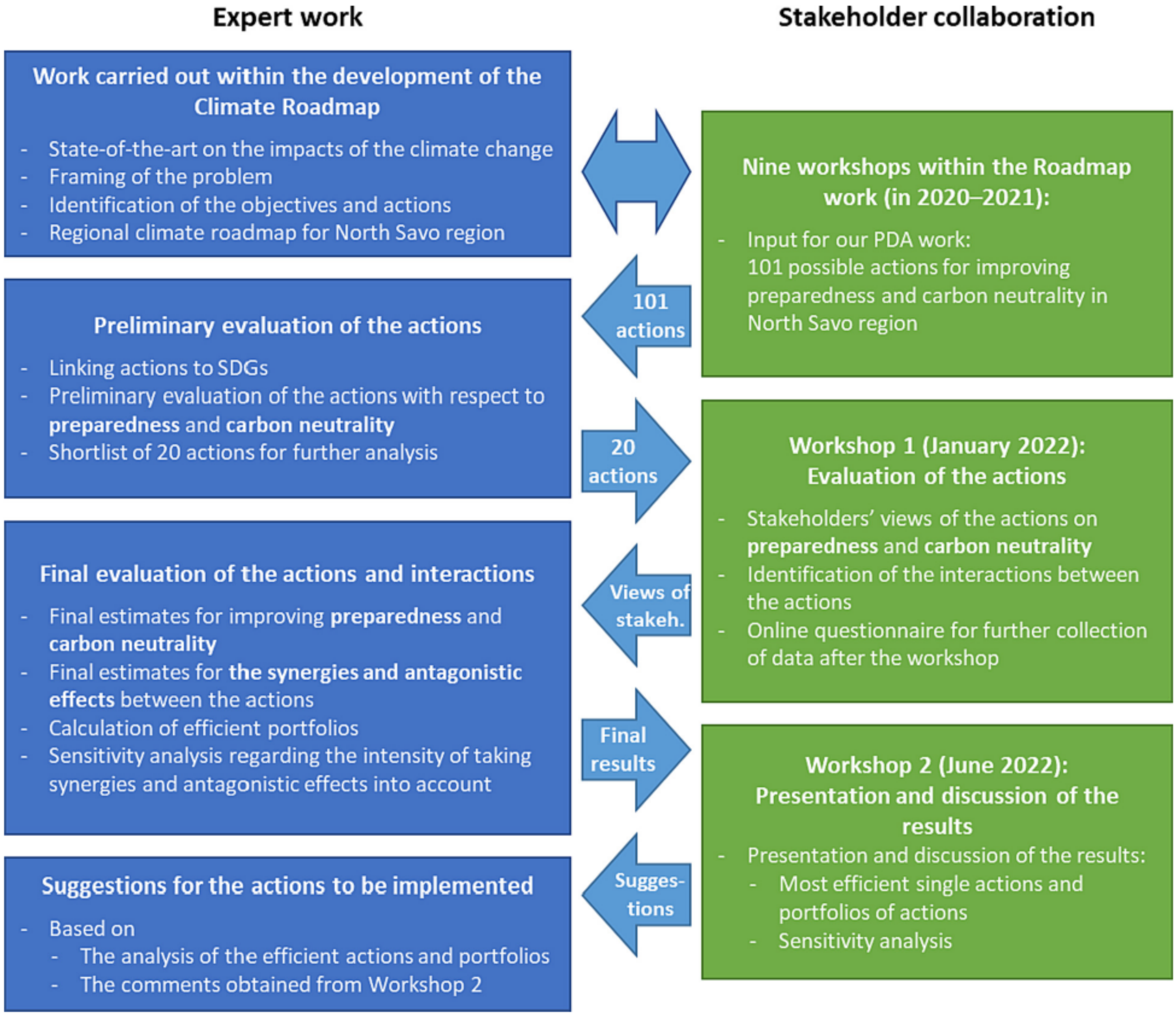

Fig. 2. The process of applying our proposed approach in the North Savo case.

Savo regional Climate Roadmap and its background calculations of greenhouse gas emissions and carbon balance. Furthermore, the North Savo regional development programme and Regional Plan 2040, as well as four scenarios established for the direction of Finland's regional development in 2040 were provided to the participants.

In the workshop, the Climate Roadmap and the Regional Plan 2040 with its climate objectives were introduced in a joint session to the whole group. Then, the preselected shortlist of the actions and background assumptions with working guidelines were introduced. The participants were divided into four working groups representing: i) energy, ii) natural resources, iii) RDI (research, development and innovation) and water, and iv) citizen preparedness and adaptation. Each group, consisting of about six participants and a facilitator, was assigned to evaluate five actions.

4.2.2.1. Stakeholders' views on the actions concerning carbon neutrality and preparedness. In the working groups, the participants first briefly introduced themselves, and then the facilitator briefly introduced the five preselected actions to be evaluated, especially their role in the Climate Roadmap work. This was followed by a general discussion on the *carbon neutrality* and *preparedness* of the actions. Each working group had two tasks. The first one was to evaluate the performances of each action $j \in \{1, \dots, 20\}$ in terms of both *carbon neutrality* ($x_1^j \in [0,4]$) and *preparedness* ($x_2^j \in [0,4]$) by answering to questions "how significant is the action in terms of achieving the *carbon neutrality* objectives of Climate Roadmap" and similarly for *preparedness* (including adaptation to climate change). In practice, the group first discussed the issue (*carbon neutrality* or *preparedness*), followed by independent evaluation of the actions by each participant. The scale for the evaluation was from 0 (not significant at all) to 4 (very significant).

4.2.2.2. Identification of the interactions between the actions. The second task was to identify and evaluate the interactions between the actions. First, discussion of the interactions was carried out action-by-action, aiming to enrich understanding of the joint effects of the actions. After the discussion, the participants independently evaluated the actions on their own. For each action $j \in \{1, \dots, 20\}$, they evaluated negative effects related to that action ($n_j \in [-4, 0]$ ranging from -4 for a very significant effect to 0 for no effect) as well as positive effects ($p_j \in [0,4]$ ranging from 0 for no effect to 4 for a very significant effect). Different opinions were encouraged to obtain as rich material as possible. This analysis also encompassed specification of the intended action, or the group of people affected, along with a brief explanation of the underlying mechanism behind the observed effects. As a part of these evaluations, the participants identified those actions that would be negatively or positively affected if a specific action was implemented. This information was quantified through binary variables $g_{jj'} \in \{0,1\}$ and $r_{jj'} \in \{0,1\}$ as follows: $g_{jj'} = 1$ denotes that action j has a positive effect on action j' and

Table 1
A shortlist of 20 preselected actions.

Selected actions	Focus area	Sector	Time scale	Most relevant SDG target
(1) Promoting the energy efficiency of buildings, the use of waste heat and the use and production of renewable energy	Fair and clean energy	Housing	Short	7.3 Energy efficiency
(2) Enabling decentralised energy production from a security of supply perspective	Fair and clean energy	Energy & water	Short	7.2 Renewable energy
(3) Development and deployment of non-combustion energy technologies and energy storage	Fair and clean energy	Industry	Short	7.2 Renewable energy
(4) Promoting the production of renewable energy, such as wind, geo-energy and solar energy	Fair and clean energy	Industry	Short	7.2 Renewable energy
(5) Improving energy self-sufficiency to prepare for energy supply disruptions	Collaborating for climate security and biodiversity	Industry	Long	7.1 Affordable, reliable and modern energy services
(6) Oil and peat are only used as maintenance security fuels in energy production	Growing carbon sinks and stocks	Energy & water	Long	12.2 Sustainable management and efficient use of natural resources
(7) Improving the climate resilience of arable farming and forests	Collaborating for climate security and biodiversity	Land	Long	15.2 Sustainable management of all types of forests
(8) Ensuring the sustainable production, use and renewal of biomass	Green growth with circular economy and sustainable use of natural resources	Land	Short	8.4 Improve resource efficiency
(9) Climate management and use of forests. The growth condition of forests is taken care of, and the development of forest carbon balances is monitored	Growing carbon sinks and stocks	Land	Short	15.2 Sustainable management of all types of forests
(10) Promoting the development of manure treatment methods and the use of manure for biogas and fertilizer production	Green growth with circular economy and sustainable use of natural resources	Land	Long	2.4 Ensure sustainable food production systems and implement resilient agricultural practices
(11) Improving flood risk preparedness and planning	Collaborating for climate security and biodiversity	Traffic	Long	13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters
(12) Supporting the green transition through financial means, taking into account the specificities of the region and security of supply	Strong climate culture	Housing	Short	9.5 Enhance scientific research, upgrade the technological capabilities of industrial sectors
(13) Improving the adaptation and preparedness of food business operators for extreme weather events	Collaborating for climate security and biodiversity	Food	Long	13.3 Build knowledge and capacity to meet climate change
(14) Make use of the area's water expertise to ensure water safety, stormwater management and water protection	Collaborating for climate security and biodiversity	Energy & water	Long	6.6. Protect and restore water-related ecosystems
(15) Improving the use of research data in agriculture and forestry to improve climate resilience and profitability and to maintain security of supply	Strong climate culture	Land	Long	13.3 Build knowledge and capacity to meet climate change
(16) Preparing for extreme weather events and their effects on the design, maintenance and upkeep of waterways	Collaborating for climate security and biodiversity	Traffic	Long	13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters
(17) Improving the security of electricity and heat supply. Preparing for extreme weather events such as strong winds, heavy rainfall and temperature fluctuations	Collaborating for climate security and biodiversity	Energy & water	Long	13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters
(18) Improving influence in different stages of decision-making	Strong climate culture	Housing	Short	10.2 Empower and promote social, economic and political inclusion
(19) Anticipating changes in mobility and designing services accordingly	Collaborating for climate security and biodiversity	Traffic	Long	11.2 Affordable and sustainable transport systems
(20) Improving stakeholder cooperation and networks on climate issues	Strong climate culture	Industry	Short	17.16 Enhance partnership for sustainable development

$r_{j\acute{j}} = 1$ denotes that action j has a negative effect on action $\acute{j}$. For each pair of actions $j \in \{1, \dots, 20\}$ and $\acute{j} \in \{1, \dots, 20\}$, the positive ($g_{j\acute{j}}$) and negative ($r_{j\acute{j}}$) effects of implanting action j to action $\acute{j}$ were given a value of 1, if any participant identified the link, and 0 otherwise.

The small groups worked for one-and-a-half hours before coming back together, followed by presentation of each groups' results and agreeing on the next steps.

4.2.2.3. Online questionnaire for further collection of data after the workshop. After the small group work, it was found that most of the evaluation data from the participants had been lost due to problems with the database of Savonia University of Applied Sciences. To support recapping of the data, the facilitators prepared summaries of the group discussions based on their notes. The summaries included visual outlines of the interactions action-by-action (similar as presented in Fig. 3 but separately for each of the 20 actions). In the visual outline, a positive effect was marked by a green line and a negative effect by a red line. Each line also included an explanation, for example, a positive effect from action "(1) Promoting the energy efficiency of buildings, the use of waste heat and the use and production of renewable energy" on action "(5) Improving energy self-sufficiency to prepare for energy supply disruptions" was given the explanation "Improvement in energy efficiency decreases the usage of energy in general, which might help in achieving energy self-sufficiency".

4.2.3. *Final evaluation of the actions and interactions*

To complete the data, the final evaluation of the actions and interactions was carried out during the three months following the workshop. The summaries of the small group facilitators (including visual outlines of the interactions and their explanations for each action) were sent to the participants, who were asked to complete them in case they found any interactions missing. Two online discussion sessions were organised during which the participants were asked to evaluate each action $j \in \{1, \dots, 20\}$ in terms of their significance for *carbon neutrality* (x_1^j) and *preparedness* (x_2^j) as well as the magnitude of *positive* (p_j) and *negative* (n_j) effects the action has on other actions. The final estimates for these variables were all calculated as averages of the participants' estimates. The estimates given by participants were quite similar to each other, and, for example, only on four cases of 80 the standard deviation of estimates was over 1. This was expected, as the given estimates were based on the discussions that aimed to seek consensus about the values. The final estimates were also presented and briefly discussed at the start of the workshop 2 to make sure that they were satisfactory to everyone.

4.2.4. Identification of efficient portfolios and sensitivity analysis

Based on the evaluations obtained from the workshop regarding each action's performance with respect to *carbon neutrality* and *preparedness*, we proceeded to identify optimal portfolios using the portfolio model developed in Section 3.2. Value of each action was computed with the additive multi-criteria value function (1) by using linear criterion-specific value function ($v_1, v_2 : [0, 4] \rightarrow [0, 1]$) and two different criterion weight vectors ($w = (0.67, 0.33)$, $w = (0.5, 0.5)$). Subsequently, the optimal portfolios we computed by maximizing the linear portfolio value function (2) subject to three different budget constraints (i.e., $\sum_{j=1}^{20} z_j = 5, 10, 15$). The aim of using two different weight vectors and three different budget constraints was to analyse the robustness of the results with regard to variations in the problem parameters.

Furthermore, we conducted an analysis to investigate the sensitivity of the resulting optimal portfolios to interactions. By utilising the data collected as described in the earlier section, we were able to assess the parameters required for capturing interactions within the portfolio model. We examined how the composition of the optimal portfolios changed as a function of the weight (β) assigned to the overall magnitude of interaction effects (see Eq. (4)).

5. Results

5.1. The most significant actions and interactions

Fig. 3 summarises the results of the evaluations for each action $j \in \{1, \ldots, 20\}$.The four numbers in parentheses after the action's name correspond to the average evaluations with regard to the two criteria *carbon neutrality* (x_1^j) and *preparedness* (x_2^j) and the magnitude of *positive* (p_j) and *negative* (n_j) effects the action has on other actions. Moreover, the affected actions are indicated by lines: A green line between actions j and j' indicates that the one of the actions has a positive effect on the other ($g_{jj'} = 1$ *or* $g_{j'j} = 1$) and a red line (with a star) indicates that one of the actions has a negative effect on the other ($r_{jj'} = 1$ *or* $r_{j'j} = 1$). A black line represents overlapping green and red lines.

The five actions rated most significant for *carbon neutrality* were Actions 3, 4, 8, 9 and 15, all having an average rating of 3.7 on the scale from 0 to 4 (the first number in parentheses after each action in Fig. 3):

- (3) Development and deployment of non-combustion energy technologies and energy storage
- (4) Promoting the production of renewable energy, such as wind, geo-energy and solar energy
- (8) Ensuring the sustainable production, use and renewal of biomass
- (9) Climate management and use of forests. The growth condition of forests is taken care of and the development of forest carbon balances is monitored
- (15) Improving the use of research data in agriculture and forestry to improve climate resilience and profitability and to maintain security of supply

These actions represent the following objectives of the Climate Roadmap: a strong climate culture, green growth with a circular economy and the sustainable use of natural resources, growing carbon sinks and stocks, fair and clean energy, and not collaborating for climate security and biodiversity.

The four actions rated the most significant for *preparedness* were Actions 7, 8, 13 and 17, all having an average rating of 4 on the scale

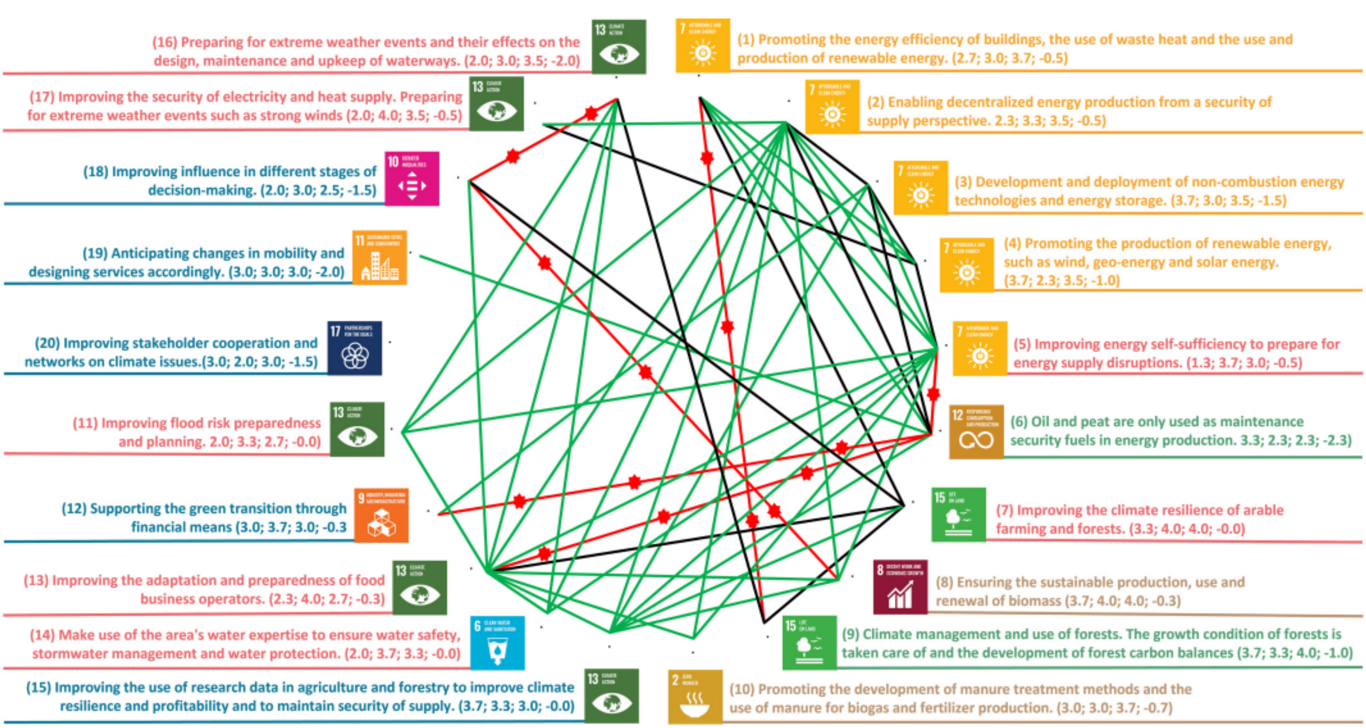

Fig. 3. Data collected from workshop participants. The four numbers in parentheses show the impact that action $j \in \{1, \ldots, 20\}$ has on carbon neutrality (x_1^j) and preparedness (x_2^j) as well as the magnitude of positive (p_j) and negative effects (n_j) on other actions. The lines indicate positive effects (green) and negative effects (red with stars) between pairs of actions (black indicates overlapping green and red lines). The font colours relate to the five main objectives of the Climate Roadmap (see Fig. 1): 1) a strong climate culture, 2) green growth with a circular economy and the sustainable use of natural resources, 3) growing carbon sinks and stocks, 4) fair and clean energy, and 5) collaborating for climate security and biodiversity.

from 0 to 4 (the second number in parentheses after each action in Fig. 3):

- (7) Improving the climate resilience of arable farming and forests
- (8) Ensuring the sustainable production, use and renewal of biomass
- (13) Improving the adaptation and preparedness of food business operators for extreme weather events
- (17) Improving the security of electricity and heat supply. Preparing for extreme weather events such as strong winds, heavy rainfall and temperature fluctuations.

These actions represent the following objectives of the Climate Roadmap: green growth with a circular economy and the sustainable use of natural resources, and collaborating for climate security and biodiversity.

The five actions with the most *positive effects* are Actions 1, 7, 8, 9 and 10, having an average rating between 3.7 and 4.0 on the scale from 0 to 4 (the third number in parentheses after each action in Fig. 3):

- (1) Promoting the energy efficiency of buildings, the use of waste heat and the use and production of renewable energy
- (7) Improving the climate resilience of arable farming and forests
- (8) Ensuring the sustainable production, use and renewal of biomass
- (9) Climate management and use of forests. The growth condition of forests is taken care of, and the development of forest carbon balances is monitored
- (10) Promoting the development of manure treatment methods and the use of manure for biogas and fertilizer production

These actions represent the following objectives of the Climate Roadmap: green growth with a circular economy and the sustainable use of natural resources, growing carbon sinks and stocks, fair and clean energy, and not collaborating for climate security and biodiversity. Note that the identified connections are not taken into account here, but only the magnitude of the positive effect.

The six actions with the most *negative effects* are Actions 3, 6, 16, 18, 19 and 20, having an average rating from −2.3 to −1.5 on the scale from −4.0 to 0 (the fourth number in parentheses after each action in Fig. 3):

- (3) Development and deployment of non-combustion energy technologies and energy storage
- (6) Oil and peat are only used as maintenance security fuels in energy production
- (16) Preparing for extreme weather events and their effects on the design, maintenance and upkeep of waterways
- (18) Improving influence in different stages of decision-making
- (19) Anticipating changes in mobility and designing services accordingly
- (20) Improving stakeholder cooperation and networks on climate issues

These actions represent the following objectives of the Climate Roadmap: a strong climate culture, growing carbon sinks and stocks, fair and clean energy, and collaborating for climate security and biodiversity. Note that the identified connections are not taken into account here, but only the magnitude of the negative effect.

Table 2 presents the optimal portfolios for different criterion weights and budget constraints, offering valuable insights into the significance of different actions. The actions always appearing in the optimal action portfolio regardless of the criterion weight or budget constraint are Actions 3, 7, 8, 9, and 15. Conversely, Actions 5, 11, 16, and 18 are absent from all portfolios with any parameter values. The criterion weights have an impact on the decision recommendations. For instance, when the maximum portfolio size is 10 actions, Action 6 is included in the optimal portfolio when $w = \left(\frac{2}{3}, \frac{1}{3}\right)$ but not when $w = \left(\frac{1}{2}, \frac{1}{2}\right)$.

5.2. *Impact of interactions on the optimal action portfolios*

We applied the portfolio model described in Section 3.2 to analyse the impacts of incorporating interactions into the decision recommendations. We employed two different approaches to estimate the coefficient $\alpha(j, j')$ from the data collected from the workshop participants (i.e., $p_j, n_j, g_{jj'}, r_{jj'}$, see Fig. 3). In the first approach, we only use the data related to whether a synergy or antagonistic effect exists between a pair of actions (lines in Fig. 3). Recall, that for all action pairs $(j, j'), j, j' \in \{1, \ldots, m\}, j \neq j'$, we use the notation $g_{jj'} = 1$ to denote the case where action j has a positive effect on action j' ($g_{jj'} = 0$ otherwise) and $r_{jj'} = 1$ to denote the case where action j has a negative effect on action j' ($r_{jj'} = 0$ otherwise). To incorporate both positive and negative effects in a single term, we define $\alpha(j, j')$ as

$$\alpha(j, j') = max\left(g_{jj'}, g_{j'j}\right) - max\left(r_{jj'}, r_{j'j}\right)$$

for all action pairs $(j, j') \forall j \in \{1, \ldots, m-1\}, j' \in \{j+1, \ldots m\}$. The coefficient $\alpha(j, j')$ can thus only take values of −1, 0 or 1, since $max\left(g_{jj'}, g_{j'j}\right)$ and $max\left(r_{jj'}, r_{j'j}\right)$ are binary. For example, if action j has a positive effect on action j' but action j' has a negative effect on j, then $\alpha(j, j')$ would be equal to 0 (i.e. black lines in Fig. 3).

To analyse the impact of the magnitude of the interaction on action-specific decision recommendations, we identified the optimal portfolios by solving the ZOLP problem (6) for V with different values of β. The sensitivity analyses were carried out using criterion weights $w = (2/3, 1/3)$ and a single portfolio constraint that allows the selection of half of the action candidates (i.e., $\sum_{j=1}^{20} z_j = 10$). In particular, we first solved the optimal portfolios for a grid of values $\beta \in \{\beta_1, \ldots \beta_{1201}\} = \{0, 0.01, 0.02, \ldots, 1.2\}$. To confirm that we did not miss any portfolios between these values we deployed the following approach: For each consecutive values β_k and β_{k+1} that yield different optimal portfolios z^k and z^{k+1}, we identified the value of $\beta^* \in [\beta_k, \beta_{k+1}]$ for which these two portfolios have equal value (i.e., $V\left(z^k\right) = V\left(z^{k+1}\right)$) and then solved the optimal portfolio for β^*. The grid turned out to be sufficiently dense, as these additional computations did not identify any new portfolios. Finally, we verified that the composition of the optimal portfolio does not change when β is >1.2. Specifically, we identified the portfolio that maximizes the total interaction effect $V_I(z)$ by modifying the objective function of ZOLP problem (6). This portfolio was identical to the portfolio that is optimal for $\beta = 1.2$.

Fig. 4 shows which actions are included in the optimal portfolios for different values of β. When $\beta = 0$, the optimal portfolio is equal to the one obtained using the linear portfolio value V_L function, which does not consider interaction between actions. A small β value significantly affects the composition of the optimal portfolio. For instance, Actions 6 and 19 are included in the optimal portfolio when $\beta = 0$, but they are replaced with Actions 13 and 2 as β increases. However, when the weight given to interaction effects exceeds the value $\beta = 0.42$, it no longer affects the optimal portfolio's composition.

In the second analysis, we estimated the coefficients $\alpha(j, j')$ by incorporating the strength of the interaction effects based on the estimates given by the workshop participants (p_j, n_j). Specifically, we computed the magnitude of the interaction effect between actions j and j' by taking the average of the positive and negative effects identified for actions j and j'. Recall that, we denote the magnitude of the positive effect that action $j \in \{1, \ldots, m\}$ has on other actions by $p_j \in [0, 4]$ and the magnitude of the negative effect that action j has on other actions by $n_j \in [-4, 0]$. With this notation, the coefficient $\alpha(j, j')$ can be defined as

$$\alpha(j, j') = \left(\frac{p_j g_{jj'} + p_{j'} g_{j'j} + n_j r_{jj'} + n_{j'} r_{j'j}}{g_{jj'} + g_{j'j} + r_{jj'} + r_{j'j}}\right) \Big/ 4$$

Table 2
Optimal portfolios for various criteria-specific weights and budget constraints.

Criterion weights	w = (2/3, 1/3)			w = (1/2, 1/2)		
Budget constraint	$\sum_{j=1}^{20} z_j = 5$	$\sum_{j=1}^{20} z_j = 10$	$\sum_{j=1}^{20} z_j = 15$	$\sum_{j=1}^{20} z_j = 5$	$\sum_{j=1}^{20} z_j = 10$	$\sum_{j=1}^{20} z_j = 15$
Action 1 (z_1)	0	0	1	0	0	1
Action 2 (z_2)	0	0	1	0	0	1
Action 3 (z_3)	1	1	1	1	1	1
Action 4 (z_4)	0	1	1	0	1	1
Action 5 (z_5)	0	0	0	0	0	0
Action 6 (z_6)	0	1	1	0	0	1
Action 7 (z_7)	1	1	1	1	1	1
Action 8 (z_8)	1	1	1	1	1	1
Action 9 (z_9)	1	1	1	1	1	1
Action 10 (z_{10})	0	1	1	0	0	1
Action 11 (z_{11})	0	0	0	0	0	0
Action 12 (z_{12})	0	1	1	0	1	1
Action 13 (z_{13})	0	0	1	0	1	1
Action 14 (z_{14})	0	0	0	0	0	1
Action 15 (z_{15})	1	1	1	1	1	1
Action 16 (z_{16})	0	0	0	0	0	0
Action 17 (z_{17})	0	0	1	0	1	1
Action 18 (z_{18})	0	0	0	0	0	0
Action 19 (z_{19})	0	1	1	0	1	1
Action 20 (z_{20})	0	0	1	0	0	0

for all action pairs $(j, \acute{j}), j \in \{1, \ldots, m-1\}, \acute{j} \in \{j+1, \ldots, m\}$. For example, if action j has a positive effect on action $\acute{j}$ with a strength of $p_j = 3.5$ and a negative effect with a strength of $n_j = -2$, and if action $\acute{j}$ does not have any impact on action j, the coefficient receives the value $\alpha(j, \acute{j}) = \left(\frac{3.5-2}{1+1}\right)/4 = 0.1875$.

Fig. 5 presents the decision recommendations for various values of β. As before, $\beta = 0$ corresponds to the situation without interactions. Thus, when $\beta = 0$, the composition of the optimal portfolio is the same as the one obtained using the model that considers only binary interactions (see Fig. 4). The optimal portfolio composition changes as β increases from 0 to 0.3, after which it stabilises and remains constant for higher values of β. Notably, the decision recommendations obtained from large values of β differ between Fig. 4 and Fig. 5. When the strengths of interaction effects are considered in the model, Actions 1 and 4 are included in the optimal portfolio instead of Actions 11 and 14, as obtained by the model that considers only binary interaction effects between actions.

6. Discussion

6.1. Applicability of the approach in practice

We tested the approach developed in this paper as a part of the Climate Roadmap for the North Savo region, and it was found to be applicable in practice. The main findings among the workshop participants were as follows. First, results emphasised the interdependencies between Action 15 ("Improving the use of research data in agriculture and forestry to improve climate resilience and profitability and to maintain security of supply") and several other actions. Thus, when implementing the actions, recent research findings should be utilised, because research continuously produces new results and understanding. For example, there is regional research related to cultivation of peat fields and plant selection, which so far has not been utilised in practice. Secondly, results also showed strong interdependencies between Action 2 ("Enabling decentralised energy production from a security of supply perspective") and several other actions. Thus, the share of renewable energy is increasing, but the examination prompted decision makers to include security of supply more deeply into analysis. This emphasises that when implementing the mitigation actions, the preparedness and adaptation actions as well as their synergies should also be taken into account. In fact, when the interactions were not considered (i.e. when $\beta = 0$), Action (2) was not included in the set of efficient actions, which further highlights the importance of considering the interactions. Thirdly, interaction between Actions 8 ("Ensuring the sustainable production, use and renewal of biomass") and 13 ("Improving the adaptation and preparedness of food business operators for extreme weather events") led to identification of importance of water related to land-based climate actions and to increase planning of catchment level climate actions. Moreover, in order to prevent antagonistic effects, it is crucial to conscientiously consider potential harm to other actions or groups of people when executing the actions (adhering to the "Do not harm" principle).

In general, the workload for participants was manageable and still produced useful information for practical decision-making. The analysis helped participants to identify several overlaps among the actions and to conclude that actions should be defined in more concrete and detailed way. Participants also agreed to examinate interactions in the future when planning and implementation the Climate Roadmap.

We also carried out a Context, Intervention, Mechanism, Outcome (CIMO; Denyer et al., 2008) analysis (complemented with Impact) to analyse the characteristics of our case study:

- Context: Interactions between 101 actions included in the Climate Roadmap to a carbon neutral North Savo region by 2035
- Intervention: A co-creation workshop method implementing evaluation of interactions and systems analysis was developed and piloted
- Mechanism: The Climate Roadmap includes actions covering five focus areas and six cross-cutting economic sectors. Although the actions were identified and selected by wide participation, they are still strongly based on sectoral expertise and lack analysis of how the actions are interrelated. The analysis of interdependencies gives an efficient set of actions when taking the most relevant pairwise actions into account. To reduce the possible imprecision of the analysis due to the approximity of the assessment, a sensitivity analysis of the results was carried out to analyse the impact of the intensity of taking the joint effects into account.
- Outcome: An approach was developed where the most obvious interactions can be identified with questions posed to the workshop experts. The analysis of interactions between the actions of the Climate Roadmap makes it possible to form insights into the synergies and trade-offs of individual actions.
- Impact: Synergies and trade-offs will be better known when putting the actions of the Climate Roadmap into practice. This is expected to

lead to better results in achieving carbon neutrality and preparedness and adaptation to climate change. Critical evaluation of the interactions – the highest synergies and antagonistic effects – between individual SDGs is expected to lead to better decision-making when prioritising actions in the Climate Roadmap, leading to higher overall impacts.

The results of the analysis were presented to the regional steering group of the project. The summary of the feedback from the members of the steering group is as follows:

– It is good that interactions are evaluated; something similar could be done for other action programmes in different organisations.
– The issues that already came up during the initial work in the preparation of the Climate Roadmap (i.e., measures that sparked discussion) also came up in this evaluation. The analysis also provided new perspectives on these.
– It is good that preliminary results were obtained at this stage, because many of the group members participated in the workshop.

Based on the evaluation of interactions and the steering group feedback, the core group of experts went through all 101 initial actions and double-checked whether any of the actions not included in the final analysis of 20 actions should still be added there afterwards. However, they could not find any actions that should clearly be added to the analysis.

6.2. The main advantages of the approach and related challenges

The main advantage of the approach proposed in Section 3 (compared to an ideal PDA process) is the reduction in the cognitive workload and resources related to the assessment of the interactions between the actions. On the other hand, the means of the proposed approach for reducing the workload (i.e., the use of a shortlist of actions, and holistic evaluation of the interactions related to each action) are all characteristics that increase imprecision in the model and consequently the possibility of biased results. The right balance between these depends very much on the case, and the decision to use the approach should thus be assessed on the basis of the needs and characteristics of the case (see also Marttunen et al., 2015). One must, however, note that in this type of case, in which the measures to be evaluated are broad in content and partly vague, the results are only indicative. On the other hand, the process itself can offer new perspectives and insights, and thus provide a fruitful basis for further discussions.

In Table 3, we compare our approach with the traditional and ideal PDA processes. Traditional PDA refers to a typical way of implementing PDA, whereas ideal PDA describes how the process should carried out in a theoretically sound way, if all the possible resources and information

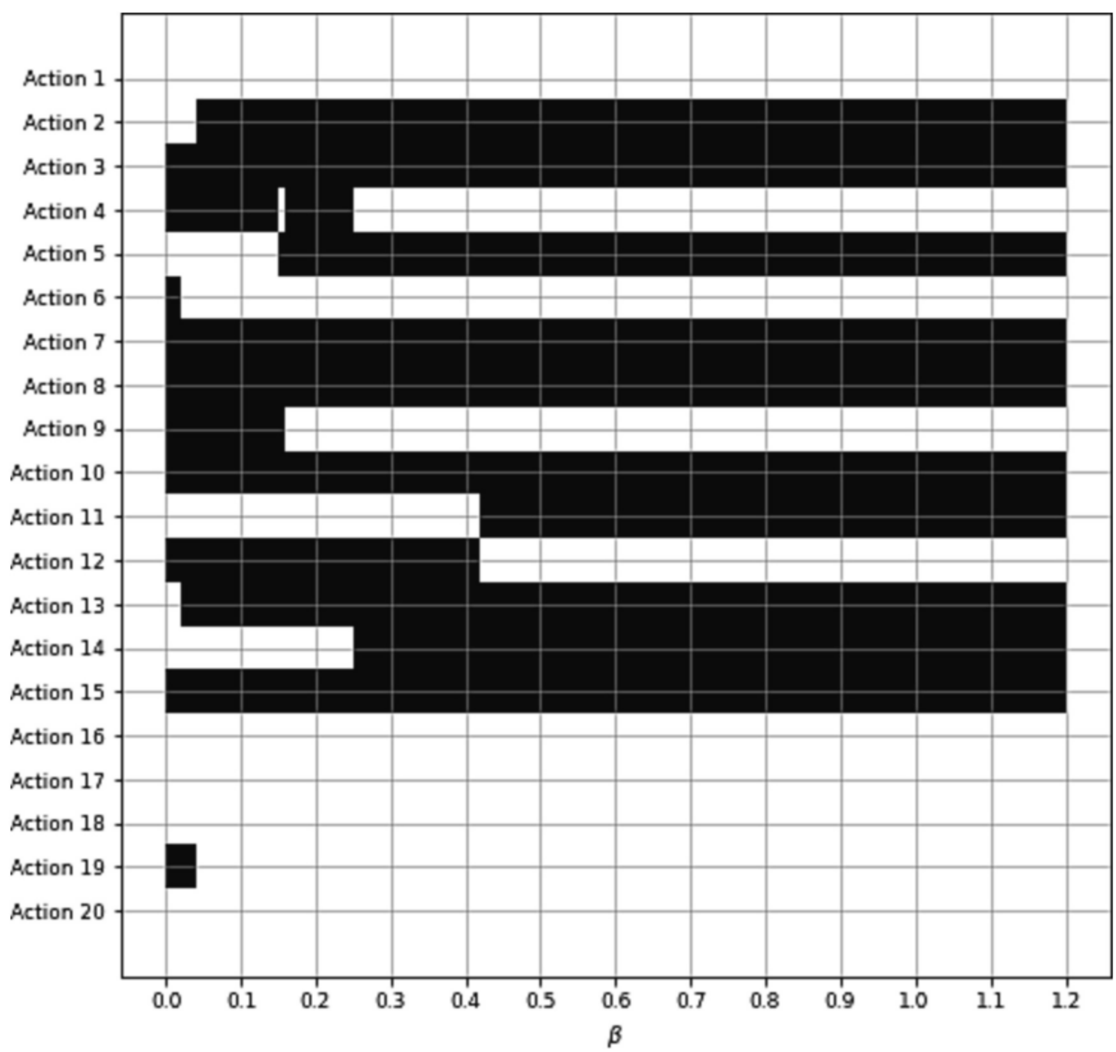

Fig. 4. Actions included in the optimal portfolio (indicated in black) as a function of the weight assigned to the interactions (β) when binary interactions are considered.

were available. For example, in traditional PDA, no interactions are typically taken into account, which reduces the rigorousness of the model. In contrast, in the ideal PDA all the interactions between all the action pairs are evaluated individually, which on the other hand would require quite an additional effort for participants. With an aim to balance between these, our approach applies the holistic evaluation of the actions and the approximate model to calculate individual interaction values for each action pair. This decreases the participants workload to feasible level but enables the systemic analysis including the sensitivity analysis with changing interaction intensity.

Within our research group, we also tested an approach in which the interactions were separately assessed for each pair of actions in our shortlist. This meant making 190 individual assessments, which would be quite a burden for a single person to carry out. To reduce the workload, we divided the task among our research group so that 5 persons estimated approximately 40 interactions each. This was also found to be an applicable approach, although there is a risk that incoherence between the individual views in the assessment may bias the results. Again, there is a trade-off between the accuracy of the results and the cognitive workload, which should be balanced according to the needs of the case. One should also note that besides pairwise interactions, there could also be effects stemming from the interaction of three or more actions simultaneously, which could not be identified in an analysis only focusing on pairwise actions.

One possible way to perform an analysis of pairwise interactions more efficiently is to first ask experts from different fields to identify the most relevant interactions from their viewpoint. After this, a workshop could be arranged in which the participants from different fields are collectively asked to decide which of the identified interactions should be included in the final model.

When linking actions to the SDGs, our initial idea was to also utilize existing analyses in which the linkages between SDGs have been identified at the target level (e.g., Pham-Truffert et al., 2020; Miola et al., 2019). However, in practice, this appeared to be impossible to implement, because the actions were at quite a general level and each of them contributed to promoting several different targets. Consequently, taking all the interactions related to all the targets to which an action contributes would not have been reasonable without explicitly specifying the intensity of the action contributing to each target. However, in cases with more specific actions, this type of approach could be useful, as the relationships between the actions and the targets are then more explicit.

In practice, the participants in the workshop were asked to separately assess the interactions between the actions and the overall positive and negative effects of each action as a whole. In most cases, they were able to carry out this task, but there were also some difficulties, especially for actions that focused on improving the processes instead of the state. For example, Action 20 (“Improving stakeholder cooperation and networks on climate issues”) focuses on the collaboration between the participants, and its direct impact on the climate is more difficult to estimate than, for example, the synergy between Actions 8 (“Ensuring the sustainable production, use and renewal of biomass”) and 2 (“Enabling decentralised energy production from a security of supply perspective”). In this respect, a third criterion related to social justice could be helpful to separate whether the impact concerns actions (“do no harm”) or people (“leave no one behind”).

We did not ask the participants to separately evaluate the interactions related to *carbon neutrality* and the interactions related to *preparedness*, but they were only asked to give one estimate for the strength of the interaction. This choice was again a result of making a trade-off between the comprehensiveness and the cognitive burden of

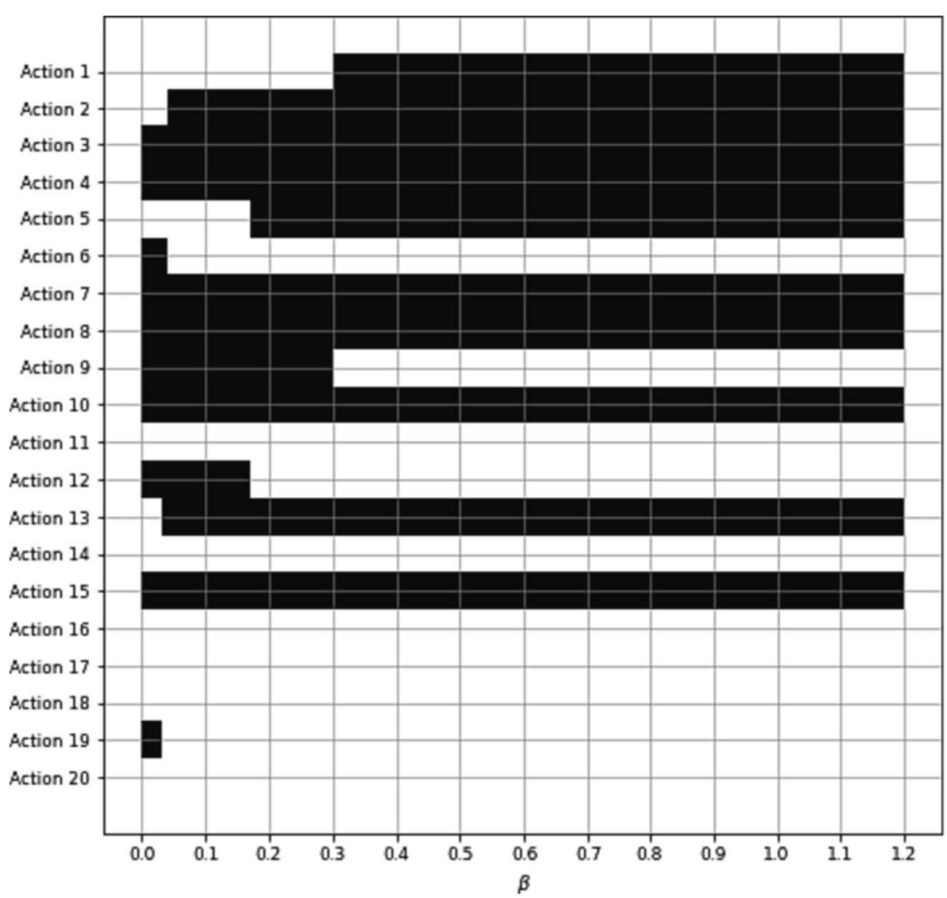

Fig. 5. Actions included in the optimal portfolio (indicated in black) as a function of the weight given to the interactions when the strengths of interaction effects are considered.

Table 3
Comparison of our approach to traditional and idea PDA.

Phase	Traditional PDA	Our approach	Ideal PDA
Selecting a shortlist of actions	No shortlist, all actions are evaluated	A shortlist of action (here 20 out of 101 actions) is selected based on experts' evaluations.	No shortlist, all actions are evaluated
Evaluation of actions and their interactions	Participants evaluate all the actions in terms of selected criteria. No interactions evaluated.	Participants evaluate the shortlist of actions in terms of selected criteria. Interactions are evaluated holistically action by action (significance of action's positive and negative interactions with other actions) and specifying the actions with which the interactions occur. Approximative model is applied to calculate the individual interaction values for each action pairs.	Participants evaluate all the actions in terms of selected criteria as well as the interactions between all the possible combinations of actions.
Calculation of efficient portfolios and sensitivity analysis	Effective portfolios are calculated for one set of criteria weights.	Effective portfolios are calculated for some different criteria weight combinations. Sensitivity of the result to the intensity of interactions is analysed.	Effective portfolios are calculated for all possible criteria weight combinations with different intensities of interaction effects.

the assessment. In future cases, it would be interesting to examine the impact of this choice on the results.

Identifying and quantifying the interactions between actions poses a significant challenge. The assessment of their impact relative to the value of individual actions is prone to bias and uncertainty. This is especially true when the assessment requires intensive involvement from decision-makers, and there are limitations in the time and effort available for accurate estimation. Based on our experience, applying the method could be cognitively much easier and less prone to biases in situations where the measures are more concretely defined than in our case, in which the actions were on quite a general level.

The sensitivity analysis carried out in this paper on the value of β provides a mechanism to examine how the portfolio changes based on the overall magnitude of interaction compared to the sum of values of the actions. In particular, if the majority of decision recommendations remain unchanged across a wide range of beta values, it indicates the robustness of the recommendations. In conclusion, our approach offers a simple and straightforward method to examine the robustness of decision recommendations, providing intuitive means to reduce the effort required for assessment.

7. Conclusions

In this paper, we developed an approach for reducing the cognitive load of modelling the interactions between the actions in PDA, which has often been a bottleneck in applying PDA in practice. As a means for reducing the burden of assessing interactions, we proposed an approach of first selecting a shortlist of actions with certain heuristics, and then carrying out the modelling of interactions only within this set of actions. We also proposed using holistic evaluation of the interactions as another means for further reducing the cognitive load of stakeholders conducting the assessment.

The approach was tested with the roadmap to a carbon neutral North Savo region by 2035, which includes 101 actions covering five focus areas and six sectors. First, 20 most significant actions of these were preselected for further analysis by six experts, and the interactions of these were assessed in a workshop of stakeholders. We conclude that the approach was applicable, and the analysis of interactions between the actions of a regional climate roadmap was able to provide insights on the most relevant synergies and trade-offs between individual actions. Besides climate actions, the approach could also be applied to other complex and challenging environmental decision-making situations related to actual megatrends, such as increasing urbanisation, air pollution, and water and resource scarcity. However, before applying the approach, it should be carefully considered whether the reduced cognitive burden of the assessment is enough to compensate for the limitations in the accuracy of the results.

In general, approaches in which interactions are separately assessed for each pair of actions appears promising, but there are also several interesting avenues for future research. There are, for example, many open questions about the detailed implementation of such an approach. For instance, it would be interesting to examine whether some type of qualitative screening could first be used to identify those action pairs that potentially produce significant interactions. Then, a detailed quantitative assessment could be focused on these pairs of actions.

In our case, identifying synergies and antagonistic effects between measures was especially challenging, because the measures were not concrete but partly rather general and objective-like. In general, the ability of individuals to assess the synergies or antagonistic effects between measures would be an interesting topic for further research. For instance, what types of challenges and cognitive biases may occur?

More research is also needed into developing suitable numerical assessment techniques for the interactions that balance between the cognitive effort required from the experts and the accuracy of the produced estimates. For instance, a 7-point verbal evaluation scale from "a very significant antagonistic effect" to "a very significant synergistic effect" might be relatively easy to apply, but transforming the resulting evaluations to numerical values that are consistent with the multi-criteria values of individual actions can be challenging. In any case, such methodological research should be accompanied by empirical studies to evaluate the performance of the developed methods and processes in real-world decision support applications.

CRediT authorship contribution statement

Jyri Mustajoki: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Juuso Liesiö:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Miika Kajanus:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Tuomo Eskelinen:** Formal analysis, Investigation, Methodology, Writing – original draft. **Saara Karkulahti:** Investigation, Writing – original draft. **Taeyoung Kee:** Formal analysis, Investigation, Methodology, Writing – original draft. **Anni Kesänen:** Formal analysis, Investigation, Writing – original draft. **Tapio Kettunen:** Investigation, Writing – original draft. **Jyri Wuorisalo:** Investigation, Writing – original draft. **Mika Marttunen:** Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

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