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An interactive decision support tool towards climate resilience

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Abstract

The study aims to enhance climate change adaptation decision-making by providing a systematic approach to leveraging previous solutions and best practices. It addresses the need for tools that enable decision-makers to identify, evaluate, and apply relevant adaptation strategies with improved climate resilience outcomes. An interactive decision support tool was developed, incorporating a knowledge base of properly encoded climate change adaptation solutions and best practices. The proposed tool demonstrates the ability to match problem descriptions with relevant cases and provide actionable recommendations. By combining case-based reasoning (CBR) and rule-based reasoning (RBR), the tool generates responses, which may include similar solutions from the knowledge base, supporting evidence-based climate adaptation decisions. Moreover, for each stored case, environmental costs and impacts are quantified in monetary terms to support informed decision-making. The integration of environmental cost quantification in monetary terms enables a more holistic evaluation of adaptation options. The proposed approach facilitates the reuse of validated solutions while incorporating environmental and economic considerations. Decision-makers can use the tool to streamline the identification and selection of climate adaptation measures that align with both environmental and economic priorities. The system's ability to automatically generate outputs based on user-defined problems has the potential to improve adaptation planning efficiency and promote sustainable practices.

Keywords: Climate resilience, Decision support systems, Ecosystem services, Environmental monetization, Hybrid reasoner.

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1. Introduction

Integrating reforms to address climate change and implement action plans for the green agenda are vital for fostering sustainability and demonstrating commitment to environmental sustainability and economic resilience in alignment with European and international standards.

EU-level initiatives and activities facilitate the sharing of experiences, partnerships, and peer learning. The successful implementation of the SDGs critically depends on the active involvement of regional, local, and civil society stakeholders, which is essential for the efficient achievement of the 2030 Agenda for Sustainable Development.

Sustainable development necessitates managing a series of risks, including those posed by climate change. Given that climate change constitutes a growing threat to development, sustainability will be more challenging to achieve for many locations, systems, and populations unless development pathways are pursued that are resilient to the effects of climate change [1].

However, there is a lack of insight among citizens regarding the accuracy of their knowledge about politicized science, such as climate change or coronavirus disease 2019 (COVID-19). In fact, around climate change, citizens are confronted with a mix of accurate information and misinformation that constantly challenges the credibility of citizens' existing knowledge [2]. In such a noisy and potentially confusing information environment, meta-knowledge could serve as a critical guide when forming beliefs supported by knowledge, particularly when unequivocal external feedback about the accuracy of knowledge is absent [3]. Thus, decision support would play a pivotal role in how individuals accumulate, process, and draw conclusions from evidence.

Despite commendable efforts and increased political and public attention to the climate change issue, accompanied by the development of corresponding strategic documents by international organizations, decision-making processes remain sluggish, and the tools available to decision-makers are limited, with results remaining incomplete.

In this paper, an interactive decision support tool (IDS4Clima) is presented that is based on properly encoded previous solutions and best practices presented in the literature and stored within a Knowledge Base. Decision support is based on a hybrid reasoner, which combines both case-based (CBR) and rule-based (RBR) reasoning. The combination of RBR and CBR has been widely used, exhibiting quite successful results [4].

Moreover, an Environmental Monetization Tool is presented as a module of the IDS4Clima, which calculates in monetary terms the environmental costs and the existing impact on the environment for each input case encoded by the user, as well as for those cases stored in the Knowledge Base of IDS4Clima. Thus, a comparison of cases, i.e., previous solutions or best practices, can be supported by IDS4Clima in monetary terms, as far as the environmental costs and the existing impact on the environment are concerned.

In the rest of the paper, we first present related Decision Support Tools (Section 2), and then we introduce the proposed interactive decision support tool (Section 3). Subsequently, we describe the accompanying Environmental Monetization Tool (Section 4), and finally, we conclude (Section 5).

2. Related Work

The objective of the Decision Support Tools evaluation does not aim to check whether a suggested solution is correct or not. Such an evaluation would be paradoxical since Decision Support Tools, by definition, deal with unstructured or semi-structured problems, and solutions for such problems are judged only as good, bad, or reasonable, instead of right or wrong [5]. The objectives of the Decision Support Tools evaluation aim to assess whether the user's needs are properly met, the system is suitable for tasks, and users perform better with the new system. From an end-user standpoint, evaluation is based on decision quality and the improvement of the decision-making process. The latter is based on the ease of use and the understanding of the suggested solution, i.e., how much "compiled knowledge" it includes. "Compiled Knowledge" is in a form that can be processed readily and efficiently by the user.

At one extreme, there are Decision Support Tools based on a taxonomy of information/solutions where the user can simply browse this information by entering his/her preferences. Such tools are domain-specific search engines. There are also Decision Support Tools based on a knowledge base, which is a collection of rule-based approaches, "Pattern→Action" rules. Such tools use an inference engine to form their response to a user query, thus providing more "compiled knowledge." On the other extreme, there are Decision Support Tools based on machine learning techniques. Such tools are, for instance, based on a "deep" knowledge of a specific domain, thus providing highly "compiled knowledge."

There are some decision support tools for supporting decision-makers in climate change and resilience pathways. Most of them are domain-specific search engines.

The interactive funding guide is a tool offered by the Covenant of Mayors [5], that presents information on the EU funding initiatives. The user forms a query by defining i) the problem (i.e., Sustainable Energy and Climate Action Plan – SECAP development, SECAP implementation (soft/hard measures), hiring of experts/preparation of bankable projects), ii) his/her type (Signatories, Coordinators, Supporters, Academia), and iii) the country (28 EU countries). The tool responds by providing funding info, useful links, and inspiring examples.

The Urban Adaptation Support Tool (UAST) [6] functions as the main adaptation resource for the Covenant community. It provides users with all the steps needed for the design and implementation of an adaptation strategy by referring to valuable guidance materials as well. It also classifies Covenant core documents, technical materials, thematic leaflets, event reports, webinar recordings, etc., while offering valuable support to both cities at early stages of adaptation planning as well as those more advanced in the adaptation process.

In "Pattern→Action" rule-based systems, the user defines the problem by inputting the existing patterns, and the tool responds by providing the triggered actions, i.e., adopting a Rule-Based Reasoning. The latter uses a set of rules (rule base) to present key information about the domain. A rule usually comprises a "Pattern→Action" or "If→Then" format, with a few or numerous conditions that need to be met to activate the execution of the rule, as well as a particular set of actions or conclusions to be added to the working memory. The inference mechanism is realized with the input to the rule base, triggering a series of rules to be executed and eventually leading to the output.

Green Factor [7] is an Excel-based tool for urban planning, developed for the iWaterproject, to ensure sufficient green infrastructure during the construction of new lots in dense urban environments. The Green Factor reflects the ratio of the scored green area to the lot area, and it can be included in relevant regulations or during the construction permit application process. When designing the lot, the targeted level of the Green Factor can be achieved by selecting from 39 green elements, such as planted and maintained vegetation or various runoff water solutions.

STDM (Support online tool for Decision-Makers) [8] focuses on work at the local and regional levels. The tool, based on the Analytical Hierarchy Process (AHP) method and a Multi-Criteria Evaluation process, is designed for use in municipal waste management. By integrating information provided by stakeholders, the tool produces a ranking of optional pathways. The user, by selecting predefined values for fields along with their relative importance, defines: i) the aim of the analysis; ii) the criteria, i.e., the guiding elements on which decisions are based; and iii) the available alternatives.

There are also several platforms developed mainly by the EU and EU agencies that involve projects addressing challenges to promote human well-being and biodiversity. In particular, initiatives focus on the protection, restoration, or management of natural and semi-natural ecosystems; aquatic systems; croplands; timberlands; or the creation of novel ecosystems. Indicative platforms, explored and consulted for the purposes of this research, are:

The European Climate Adaptation Platform Climate-ADAPT [6] is developed by the European Commission and the European Environment Agency (EEA), maintained by the EEA with the support of the European Topic Centre on Climate Change Impacts, Vulnerability, and Adaptation (ETC/CCA). It includes information on EU, national, and transnational adaptation strategies and actions, case studies, and potential adaptation options and tools that support adaptation planning. The content of the platform is organized by: i) EU Adaptation Policy, Sectors, and Regional Policy; ii) countries (transnational regions, cities); iii) Knowledge (topics, data, indicators, research, etc.); iv) European Climate and Health Observatory; and v) Networks.

The Nature-based Solutions Initiative NbS [9] is a research program aimed at formulating policy and practice on nature-based solutions through interaction between policymakers and practitioners. The project's mission is to enhance understanding of the potential of NbS to address multiple global challenges while supporting ecosystem health and respecting the rights of local communities. The platform also provides an interactive map of best practice examples of Nature-based Solutions around the globe, showcasing how working with nature can benefit both biodiversity and people, while addressing climate change. The platform contains NbS cases demonstrating their effectiveness in climate mitigation and adaptation, while delivering positive ecosystem health and socioeconomic outcomes.

The circular economy platform [10] is an EU-wide interactive initiative driven in collaboration with European civil society. The platform serves as a forum for stakeholders to exchange and scale up effective solutions while addressing specific challenges. The platform connects existing initiatives at local, regional, and national levels, supporting the implementation of the circular economy. It seeks to enhance collaboration among stakeholder networks by facilitating the exchange of expertise, good practices, knowledge, and lessons learned. In addition, the platform identifies barriers (social, economic, and cultural) that hinder the transition to a circular economy with the goal of informing policy at all levels of governance.

Oppla [11] serves as the EU Repository for Nature-Based Solutions and a knowledge marketplace that integrates the latest insights on natural capital, ecosystem services, and nature-based solutions. Its purpose is to streamline the process of sharing, acquiring, and generating knowledge to improve environmental management. As an open platform, Oppla is tailored to meet the diverse needs of scientists, practitioners, and organizations as well as public, private, and voluntary sectors. It welcomes participation from all, encouraging a collaborative community approach.

The Climate Innovation Window [12] intends to serve as a key portal for innovations in climate change adaptation. The main objective is to reinforce the knowledge among innovators and end-users in enhancing resilience to floods, droughts, and extreme weather events, as Europe is particularly vulnerable to these natural hazards, and mounting evidence indicates that damages will likely increase. However, evaluations reveal that there is significant potential for risk reduction through effective adaptation strategies.

WeADAPT [13] constitutes a central hub for professionals working on climate change adaptation, providing access to a comprehensive collection of articles, cases, projects, and practices regarding climate change assessment and resilience.

Sustainable Sanitation Allianc [14] stands as an informal network of partners and individual members united by a shared vision of sustainable sanitation and a commitment to advancing the Sustainable Development Goals, particularly SDG6. Established in early 2007, SuSanA connects its members to a diverse community of experts, facilitating the exchange of ideas, promoting innovation, and contributing to policy dialogue through collaborative publications, meetings, and initiatives. The platform features a comprehensive project database and discussion forum, serving as a valuable resource for fostering sustainable sanitation systems.

The platform for ocean conservation [15] emphasizes ocean advocacy while fostering connections with nature, alongside efforts to protect and restore critical marine habitats. By adopting an optimistic, solutions-oriented approach, focused on both physical and emotional connections with nature, the initiative is based on two primary fields: behavior change and habitat restoration. The goal is to engage a wide audience by creating accessible and inclusive experiences that highlight the ocean's richness and diversity. These experiences are carefully designed to cultivate a deep appreciation for the ocean, with the aim of inspiring a strong desire to protect it.

3. The Proposed Interactive Decision Support Tool

A Decision Support Tool is software developed to support analysts and decision makers in making better decisions, faster. Regardless of the domain, the technical, economic, human, and social factors that a climate change adaptation pathway may face each bring their own unique costs, values, and feasibilities. Making the right decision and choosing the proper course of action can be challenging for decision makers since they usually do not have all the data available at their disposal. This issue can still be complex even when decision makers have some insights but lack the software to make connections between the data to see the full picture. Decision support tools merging deep analysis with powerful prediction capabilities improve the way they approach information, insights, and the surrounding contexts.

The proposed Interactive Decision Support Tool (IDS4Clima) is a knowledge-based intelligent information system. Its objective is to collect, organize, process, and exploit solutions and best practices, properly encoded and stored in its Knowledge Base, in order to provide valuable advice to decision makers in the form of ready-to-use workflows, which serve as climate change adaptation pathways. The Interactive Decision Support Tool is developed as a unique system based on Artificial Intelligence techniques designed to bridge forecasts and conclusions within a qualitative analysis and to provide an opportunity for the improvement of the quality and efficiency of climate change adaptation pathways. The Interactive Decision Support Tool will offer an easy and time-saving way of getting expert advice regarding the application of certain solutions to specific climate change problems and various pollution mix issues.

End-users of the proposed Interactive Decision Support Tool are decision-makers, policymakers, experts, public authorities, stakeholders, as well as the wider public and the media.

The Knowledge Base is built by inserting both site-specific and general information. To build in-site-specific information, properly encoded solutions and best practices are gathered from former projects (H2020, EIT KICs, LIFE+, Structural Funds Programmes of the EIB and the EBRD, etc.), on suitable circular water and nutrient use cases, cascading biomass utilisation strategies, decentralised resource conversion, civic society participation, etc. General information in the Knowledge Base will be built by inserting general guidelines extracted from various adaptation strategies and action plans.

Depending on the problem described and entered by the end-user, the tool's response is automatically composed. The response consists of i) automatically formed information/consultations suggested for application to the problem at hand, and/or ii) certain similar solutions and best practices stored in the Knowledge Base, which would be properly revised to adapt to the described problem at hand. The user evaluates the automatically formed solution, and the Interactive Decision Support Tool stores the evaluations so they can be used for future suggestions by the tool. Negative evaluations form a set of exceptions stored in the Knowledge Base. The successive application of solutions suggested by the tool can also be inserted and stored in the Knowledge Base. Thus, the performance of the Interactive Decision Support Tool will increase through its own usage.

3.1. The Hybrid Reasoner of IDS4Clima

The IDS4Clima Interactive Decision Support Tool adopts a hybrid reasoner to suggest appropriate previous solutions or best practices to the user. The hybrid reasoner is based on combining Rule-Based Reasoning (RBR) and Case-Based Reasoning (CBR). The combination of RBR and CBR has been widely used and has demonstrated successful results [4].

Rule-based reasoning (RBR) uses a set of rules (a rule base) that represent general knowledge about a domain. A rule usually has an 'if-then' format, with several conditions that need to be satisfied for the rule to be activated and a set of actions or conclusions that are added to the working memory when the rule is executed. Inference takes place by introducing the input to the rule base, causing a chain of rules to be triggered and executed that eventually lead to the output [16]. RBR is appropriate when there is a clear model of the domain or when there are available experts who can represent it in the form of rules. Case-based reasoning takes advantage of past cases stored to deal with new, similar cases. The inference is usually performed in four phases, known as the CBR cycle [17]: retrieve, reuse, revise, retain, as depicted in Figure 1. Retrieval concerns finding in the set of stored cases one or more cases that appear to be the most similar to the new case. Reuse is concerned with using the retrieved, relevant cases to propose a solution for the new case. Revision concerns the validation of the proposed solution by testing if it solved the problem at hand. Retain decides if the new case is useful enough to be stored in the pool of past cases.

Such a combination of Rule-Based Reasoning and Case-based reasoning has been widely used, exhibiting quite successful results [4] due to the combination's complementary capabilities/characteristics [18]. CBR-RBR hybrids are used in systems so that the integrated method can potentially take advantage of the positive aspects of both constituents while minimizing their negative aspects. More specifically, the IDS4Clima adopts a recent specific hybrid reasoner presented in [19]. The latter is based on a combination of tightly sequential and embedded models, where RBR and CBR are combined to improve the decision success rate of the CBR component, which is the main component. RBR is used to enhance the information of input cases, which are then passed to the CBR model. To our knowledge, the proposed Interactive Decision Support Tool is the first one to adopt a hybrid reasoner for supporting decision-makers in climate change/resilience pathways.

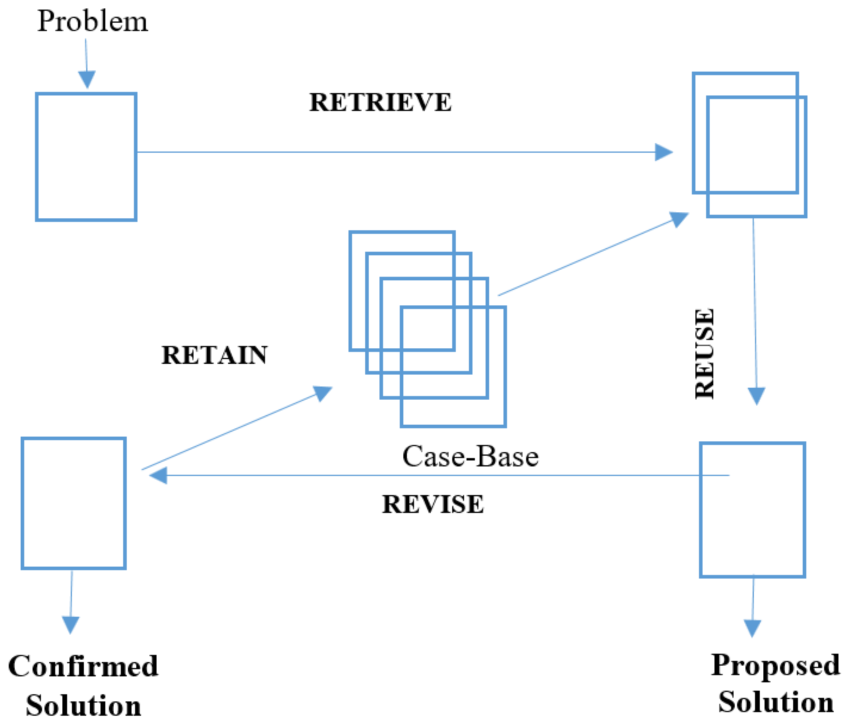

Figure 1.
CBR cycle Aamodt and Plaza [17].

3.2. The Rule Base of IDS4Clima

"If-Then" rules seem to be one of the most common forms for expressing various types of domain knowledge. Such rules are usually constructed by knowledge engineers from human knowledge. Rule-based Expert Systems, consisting of a knowledge base and an inference engine, infer useful conclusions from the rules in the knowledge base and observation facts provided by users. "If-Then" rules are curated by domain experts in any given science field, and those who master the knowledge that is traditionally in demand are very few worldwide. Thus, there is a Knowledge Acquisition Bottleneck in the quest to build Rule-based Expert Systems, since there exists a serious shortage of human resources [20, 21].

Thus, lately, the new trend is to let the system 'discover' the rules by crunching as much data as possible and by applying powerful machine learning techniques [22].

The Rule Base of IDS4Clima consists of 48 rules established by applying Association Rule Mining to the Case Base of IDS4Clima. More specifically, the Apriori algorithm is applied to an input database containing the fields included in the Case Base of IDS4Clima, except for the fields storing the *Implementation Steps*.

Association Rule Mining was preferred over Classification, since we aimed to extract as many general rules as possible concerning all the input fields. Classification is asymmetric with respect to attributes, since in classification we aim at predicting the value (class) of a special, user-defined goal attribute based on the values of all the other (predictor) attributes. By contrast, Association Rule Mining is symmetric with respect to attributes, since no attribute is given special treatment, i.e., any attribute can occur either in the rule antecedent or in the rule consequent [23].

More specifically, the set of association rules is extracted by setting the minimum support to 5% and the minimum confidence to 90%, since there are only a few cases, while the domain of most case attributes is large. For instance, such a rule is:

IF
ADAPTATION_CATEGORY=Ecosystems_based_adaptation_options and
REGION_TYPE=Island AND CC_MITIGATION=Positive
Then
ADAPT_SECT=Water_management

A publicly available folder (https://github.com/vutsinas/IDS4Clima) has been created, including an Excel file with the set of rules of the Rule Base of IDS4Clima.

3.3. The Case Base of IDS4Clima

The Case-Based Reasoner is the main component of the proposed tool. Given an input, after it is enhanced by the RBR layer, the CBR layer detects the most relevant cases from the stored ones in the knowledge base. In the tool, a case encapsulates all the relevant information regarding a specific climate change adaptation initiative. Based on the information provided through the tools and platforms explored (Section 2), the stored cases are derived from cases identified as good practices successfully implemented in response to climate change-related challenges. These cases detail the specific adaptation actions undertaken, with careful consideration of critical aspects such as synergies and trade-offs with mitigation measures, the involvement of civil society, and regional particularities etc. The attributes associated with each case are grouped into those that refer to: *Adaptation Sector, Region type, Problem, and Solution features*. For example, *Region type* attributes encompass policy-relevant dimensions such as geographical features, governance context, and whether the solution is localized or applicable at a broader scale.

The Case Base of IDS4Clima (CB) is populated with 100 such cases, concerning real projects in various fields on climate resilience[1], directly inserted in CB (66% from section 2 platforms - 46 cases from NbS, 9 cases from Climate-Adapt, 4 from Climate Innovation Window, 4 from Susana, 2 from Oppla, 1 case from Ocean conservatory platform – and 34% cases include other relevant projects). A publicly available folder (https://github.com/vutsinas/IDS4Clima) has been created, including an Excel file with analytical information about the set of cases of the Case Base of IDS4Clima.

Given the large number of different attributes that represent a case and the fact that each case may contain multiple parallel and sequential sets, the comparison between two different cases, i.e., to calculate a representative overall similarity measure, was one of the challenging and complicated parts of the tool. It required a lot of fine-tuning to achieve optimal results.

In order to calculate an overall similarity measure, during the comparison of two cases, most of the attributes of a case are taken into account. For each of the considered attributes, a different method may be used to determine similarity, based on its type.

To describe the problems, need adaptation, an individual can select attributes from an entry form such as *adaptation sectors categories, region type, country, intervention type, and climate change impact addressed*. Most of the attributes taken into consideration in calculating case similarity concern the representation of cases. Each specific *case* is represented by twenty-four (24) attributes organized into five groups: *Adaptation Sector, Region, Problem data, Interventions, Improvements, and Implementation Steps*.

The group *Adaptation Sector* is used to describe the sectors within which several projects have been implemented, sectors crucial for climate change resilience. The group *Region* comprises both a continent and a country. The group *Problem data* refers to an ontological tree including several classes to describe the risks and the resources affected by the problems. The class includes sub-classes and sub-sub-classes to define the problem more accurately. The group of *Interventions* categorizes interventions into four (4) groups: *Food Protection, Management, Protection, and Restoration*, each of which includes multiple values to define more accurately the intervention selected. In addition, *the class of Improvements* also includes thirteen (13) *sub-classes* for defining the positive aspects of the applied solutions, such as improvements related to water, soil, agricultural advancements, local community development, energy saving, preventive actions for nature, etc.

The last group of case attributes concerns some of the steps that have been identified while implementing the solutions of the projects. The steps, referring to the initiatives undertaken, contain seven (7) attributes, namely as step 1, step 2, step 3, etc., that have been applied not necessarily in a chronological series but also in parallel. These steps may refer to considerations related to mitigation measures, civil society involvement, education, training programmes, etc., which are significant factors for the success of the solution.

In the CB, apart from categorical attributes, such as the *Organisation Type* and *Funding*, there is also a numerical attribute related to the monetization tool, described in Section 4, the *Cost of the solution (when indicated)*. The categorical case-attributes are assigned a value as a single term from the ontology created to precisely describe the problem data and solutions' fields. For these attributes, similarity is obtained based on the distance of the terms in the ontology.

There are also numerical case-attributes and three multivalued attributes. The attribute referring to *problem data* accepts up to three values, the attribute referring to *improvements (or avoidance of failures)* accepts up to four values, while attributes referring to *steps* for the implementation of the solution accept up to seven values.

3.4. The Architecture of IDS4Clima

The proposed Interactive Decision Support Tool is a knowledge-based intelligent information system. Its objective is to collect, organize, process, and exploit solutions and best practices, properly encoded and stored in its Knowledge Base, in order to provide valuable advice to decision makers in the form of ready-to-use workflows, which serve as climate change adaptation pathways. The Knowledge Base is built by inserting both site-specific and general information. To build site-specific information, properly encoded solutions and best practices are gathered from former projects. General information in the Knowledge Base is built by inserting general guidelines extracted from various adaptation strategies and action plans.

The architecture of the proposed model (RBR, CBR, PM) is depicted in Fig.2.

[1]after processing real cases characterized as good practices as mentioned above.

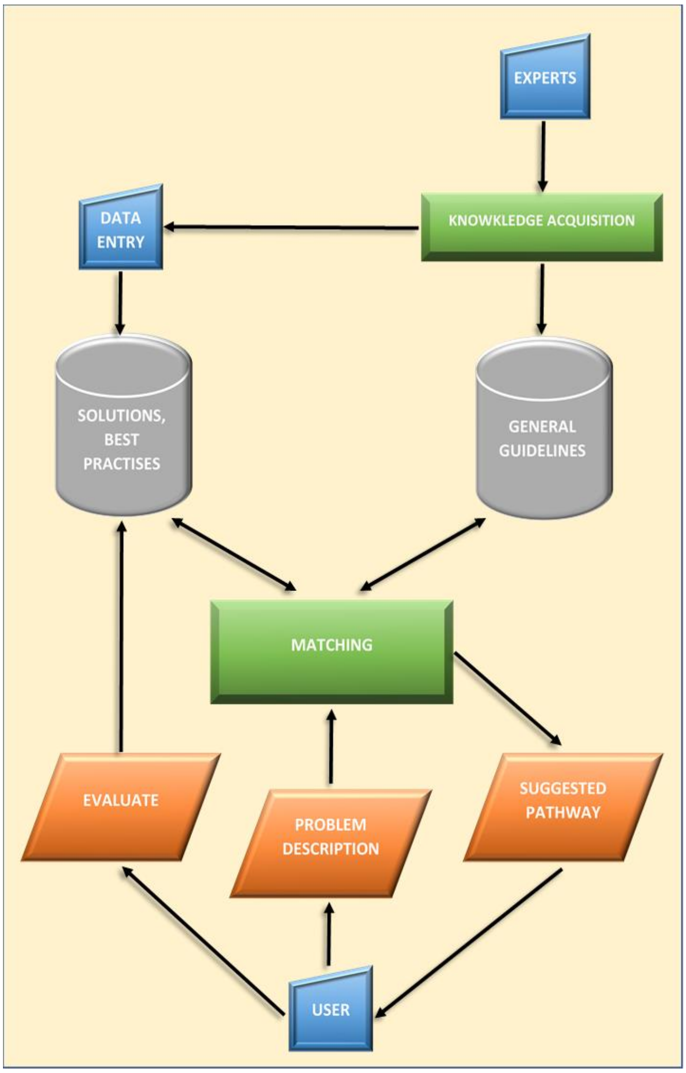

Figure 2.
The architecture of the interactive decision support tool.

The performance of the Interactive Decision Making Tool is based on the adequacy of its Knowledge Base, since the latter has embedded experts' knowledge as an internal representation of the characteristics of solutions and best practices. Those characteristics will be compared to the characteristics of the problem at hand. Given the large number of different features that represent a problem, best practice, or solution, the comparison between two different scenarios to calculate a representative overall similarity will be one of the most challenging and complex parts of the Interactive Decision Making Tool.

As stated in the previous section, when we have different types of attributes in the cases, *hybrid similarity metrics/methods* are required, which include different metrics for different types of attributes. In IDS4Clima, the following metrics, each for a different type of attribute, are adopted:

For *numerical attributes*, we use the normalized distance between two values of numerical attributes [24].

$$Sim\_num(c_{ik}, c_{jk}) = 1 - |c_{ik} - c_{jk}|/(c_i^{max} - c_i^{min}) \quad (1)$$

Where c_{ik}, c_{jk} denote the values of attribute k in cases c_i, c_j, respectively and c_i^{max}, c_i^{min} represent the maximum and minimum values of attribute k, respectively.

For *categorical attributes*, we use the *Eskin similarity* [25], between the two categorical values:

$$Sim\_cat(c_{ik}, c_{jk}) = \begin{cases} 1, & c_{ik} = c_{jk} \\ \frac{n_k^2}{n_k^2+2}, & c_{ik} \neq c_{jk} \end{cases} \quad (2)$$

Where $n_k$is the number of different values of attribute k.

For *multivalued attributes*, we use the *Jaccard similarity* [26] between two values of multivalued attributes:

$$Sim\_multi(c_{ik}, c_{jk}) = 1 - \frac{A \cap B}{A \cup B} \quad (3)$$

Where $A = \{c_{ikq} | c_{ikq} \in c_{ik}$ and $c_{ikq} \in$ domain$(k)\}$ and $B = (c_{jkq} | c_{jkq} \in c_{jk}$ and $c_{jkq} \in$ domain$(k))$.

For ontological attributes, we use a function of node distance within a tree structure [27] between two values of attributes that are represented by nodes of a given ontology:

$$1 - d(c_{ik}, c_{jk}) \quad (4)$$

Where

$$d(c_{ik}, c_{jk}) = \frac{1}{fl(c_{ik}, c_{jk})} \times Average\left(\frac{l(c_{ik}) - fl(c_{ik}, c_{jk})}{max(p(c_{ik}))}, \frac{l(c_{jk}) - fl(c_{ik}, c_{jk})}{\max(p(c_{jk}))}\right) \times \left(\frac{p(c_{ik}, c_{jk})}{\max(p(c_{ik})) + \max(p(c_{jk}))}\right) \quad (5)$$

Where c_{ik} and c_{jk} represent two nodes in the ontology, $fl(c_{ik}, c_{jk})$ is the level of the nearest common father node of them, $l(c_{ik})$ is the level of node c_{ik}, $\max(p(c_{ik}))$ is the length of the maximum path starting from the root to a leaf and containing node c_{ik}, and $p(c_{ik}, c_{jk})$ is the length of the directed path (number of edges) connecting c_{ik} and c_{jk}. The first part ($1 / fl(c_{ik}, c_{jk})$) supports the postulate suggesting that the distance between terms/values that represent more specific concepts must be smaller (i.e., less dissimilar) than the distance between terms/values that represent more general ones. The second part supports the postulate suggesting that the more general a concept's specifications are, the more similar they are. Finally, the third part supports the postulate suggesting that the distance between c_{ik} and c_{jk} must be smaller as the maximum path containing c_{ik} and c_{jk} becomes larger.

To calculate the Overall Similarity(i,j), we consider equal weight for each attribute similarity a ($WEIGHT_a = 1$).

The input includes the initial facts for the inference system, entered by the user. The RBR layer provides enhanced input to the CBR layer. The middle and last layers constitute the embedded processing model, where the PM layer participates in the retrieval part of the CBR by enhancing the result.

In a more formal way, let *FS* be the set of given (initial) facts: $f_1, \ldots, f_n \in FS$. Then, a subset *TRB* of *RB*, the rule base of the RBR component, are triggered: $r_1, \ldots, r_m \in TRB \subseteq RB$. Those rules represent general knowledge provided by domain experts. The triggered rules produce a set *AFS* of additional facts (i.e., the produced consequents of $r_1, \ldots, r_m$): $af_1, \ldots, af_m \in AFS$, which further describe or enhance the input. The enhanced input set $EFS = FS \cup AFS$, derived during this first step, is then used as input to the CBR layer. The CBR layer retrieves from $CB = \{c_i \mid c_i = (c_{i1}, \ldots, c_{ip})\}$ the case base of the CBR layer, a set *RCB* of the most relevant stored cases: $c_1, \ldots, c_t \in RCB \subseteq CB$.

The user, by filling in a form to select the basic criteria related to the problem or the case concerning climate change resilience and selecting fields regarding the adaptation sectors, the region type, the scale of the project, and the type of organization that managed the project or case, triggers the retrieval of similar cases from the case base.

After careful examination of the projects and cases presented in the open sources as defined in the previous section, and a thorough analysis of the processes and initiatives, a knowledge base of cases has been developed.

By analyzing further data and steps of the projects already undertaken in climate change resilience, an ontology was also structured, containing certain characteristics to describe more accurately the conditions or the situation of the problem as well as solutions' characteristics. Indicatively, fields such as the *problem-related risks* (*state-related risks, society-related risks, climate-change-related risks*), *natural disasters risks*, *natural resources risks* as well as solutions fields such as agriculture improvements, improvements related to soil, improvements related to water, energy saving, local community advancements, urban sanitation improvements, preventive actions for nature, etc. (see also section 3.2) are included in the ontology to more accurately describe the problem identified and retrieve, after the similarity measures have been applied, the best matching solution-case from the case base.

3.5. An Example of Applying IDS4Clima

The IDS4Clima is a knowledge-based intelligent information system. The system's functionality is mainly based on responses to queries posed by users (decision-makers, policymakers, experts, public authorities, local authorities' managers, consultants, researchers, and other stakeholders). A specially designed form facilitates users to pose queries, i.e., input problems concerning climate change. In general, taking into consideration the problem description, the system searches in the Knowledge Base for similar cases, i.e., previous solutions or best practices, and, after processing, the system returns the similar cases to the user.

Table 1.
Simplified cases.

Case id	Adaptation Category	Adaptation Sector	Region Type	Climate Change Mitigation	Problem Data	Intervention
052	Ecosystems-Based Adaptation Options	Water Management	Island	Positive	Need to create a resilient ecosystem	Water and Fertigate an agroforestry field
099	Ecosystems-Based Adaptation Options	Water Management	Island	Positive	Need to create a resilient ecosystem	Increasing green space area, using adapted plants and planting methods.
051	Ecosystems-Based Adaptation Options	Water Management	Island	Positive		Produce sweet water from salt water
053	Ecosystems-Based Adaptation Options	Water Management	Island	Positive		Produce sweet water from salt water

In order to evaluate the proposed tool, a standalone experimental application is developed which is freely available through the link: https://aigroup.ceid.upatras.gr/hybrid. Also, a publicly available GitHub folder (https://github.com/kkovas12/hybrid-pavefs) has been created, including the code of this application.

In the following, we demonstrate the use of IDS4Clima by presenting an example. We consider four of the cases stored in the CBR component of IDS4Clima. To simplify the example, we represent the cases using only six attributes, shown in Table 1, since there are many attributes needed to represent a case in the system (see Section 3.3).

Suppose that the user inputs the problem shown in Table 2, properly encoded. The example is similarly simplified, in the sense that only a subset of six features is used to represent it.

Table 2.
Selected features.

Feature Value	Type	Weight
Adaptation Category	Categorical	0.2
Region Type	Categorical	0.2
Climate Change Mitigation	Categorical	0.2
Problem Data	Multivalued	0.2
Interventions	Categorical from Ontology	0.2

The Ontology for the field "interventions" is depicted horizontally in the following:

1. Root.
2. Food Production.
3. Produce salt.
3. Produce sweet water from saltwater.
2. Management.
3. Changing lives at the local level and stimulating good governance practice.
3. Compensation paid by insurance companies. Insurance companies paid annual compensation for damages to insured buildings caused by urban and river flooding.
3. Develop and strengthen the integration in urban planning projects.
3. Education on the impacts of climate change on health.
3. Integration in urban projects.
3. Raising awareness of multifunctional green and blue infrastructure.
3. Solution with the active participation and acceptance of the local population.
3. Suitable for commercial shipping.
3. The Flood risk management approach suggested by the Flood Directive (2007/60/EC), focused on prevention, protection, and preparedness strategies.
2. Protection.
3. Address the causes and consequences of the Urban Heat Island Effect.
3. Address the urbanization.
3. Build forest resilience.
3. Consequences for the environment and the health of the population.
3. Counter the effects of deforestation by tobacco farming.
3. Counter the effects of soil degradation.
3. Counter the impacts of drought, land degradation, and desertification, which all threaten food security in the area.
3. Hydraulic infrastructure for an advanced treatment of wastewater as a defensive tool against forest fire risk.
3. Lower temperature.
3. Water and fertigate an agroforestry field.
2. Restoration.
3. Cheap water supply to remote areas with no other water supply.
3. Designing effective solutions to pluvial flooding, based on solid data, in the interest of local authorities.
3. Increasing green space area, using adapted plants and planting methods.
3. Regulation of the hydrological cycle and water flow.
3. Restoring biodiversity by consolidating green and blue infrastructure.
3. Solution focused on the distribution of temperature and cold air flows because of the high sealing degree.

Note that each case corresponds to a description of an event concerning certain features included in the database with specific successful interventions for these case-features. The "Adaptation Sector," "Region Type," and "Climate Change Mitigation" features refer to the individual case that would be drawn from the cases database. The features "Problem Data" and "Intervention" describe the solution.

The reasoning procedure starts by inserting the input incident to the system. As an example, we consider the following input:

Adaptation Category = "Ecosystems-based adaptation option"
Region Type = "Island"
Climate Change Mitigation = "Positive"
Problem Data = "need to create a resilient system"
Interventions = "Water and Fertigate an agroforestry field"

The first step of the inference procedure is to run the RBR component, using the rules shown in section 3.2. The conditions of the following rule R15 are met:

IF
ADAPTATION_CATEGORY=Ecosystems_based_adaptation_options and
REGION_TYPE=Island AND CC_MITIGATION=Positive
Then
ADAPT_SECT=Water_management
Therefore, the rule is triggered, and the input is extended with the information:
Adaptation Sector = Water Management.

Then, the CBR component is executed, and it compares the input against all the cases shown in the Cases-Database. The case with the highest match is case 052. In the publicly available folder (https://github.com/vutsinas/IDS4Clima), an analytical calculation of similarities is shown.

Thus, the output of the IDS4Clima system is the value of "Suggested Intervention" for case 052: SUGGESTED Intervention = Water and Fertigate an agroforestry field. The system will identify and retrieve the most relevant case matching the user's query, providing extended and more detailed information. This information will serve as a resource to assist the user in making well-informed decisions based on relevant precedents, contextual insights, and supporting data.

In another stage, when the process mining component is activated, the process model can be used to indicate the path of enabled transitions, which predicts a possible series of implementation steps for the intervention solution.

4. Environmental Monetization Tool of IDS4Clima

IDS4Clima includes a specific tool that supports environmental monetization of solutions and best practices, which can provide an assessment of these solutions and best practices during decision support. This tool is based on the values of the field concerning the improvements achieved in a certain case. The domain of the "improvement" field consists of about 130 different values, grouped into 13 categories: Agricultural Improvements, Awareness Raising & Training, Climate Change Resilience, Complementary Actions, Energy Saving, Improvement Actions, Improvements Related to Soil, Improvements Related to Water, Integration, Local Community Advancements, Money and Time Saving, Preventive Actions for Nature, Urban Sanitation Improvements. To each such field value, a different methodology is assigned for the calculation of the environmental cost. Thus, depending on the field value, the user is asked to enter a certain set of parameters. Then, based on these parameters, the environmental cost is calculated.

There are many software tools [28] that can support Environmental Management Accounting. However, most of them are calculators in the form of applications or spreadsheets [29] for measuring petroleum use, energy efficiency in buildings, emissions, carbon footprint, performance of steam systems, etc.

Some tools support the application of certain related methodologies, such as Life Cycle Analysis, either commercial (e.g. [30]) or freeware (e.g. [31]). Following extensive research, tools supporting the automation of a specific Environmental Management Accounting using certain related methodologies (such as Material Flow Cost Accounting – MFCA, Environmental Full-Cost Accounting – EFCA, Activity Based Costing -ABC, etc.) do not exist, to our knowledge, thus far. EMFACT [32] seems to be closer to such an approach, automating an MFCA-like methodology. There are also tools that support decisions concerning the selection of strategies/methodologies, e.g., the EPA Ecosystem Services Tool Selection Portal [33].

Most of the work towards monetary valuations concerns protocols like the Natural Capital Protocol of the Capitals Coalition [34] and the report "Monetary valuation of ecosystem services and ecosystem assets for ecosystem accounting" [35].

There are also databases, including precalculated monetary evaluations, such as the Ecosystem Services Valuation Database (ESVD) - Value Transfer Tool (Foundation for Sustainable Development and Brander Environmental Economics) [36], the platform "ARIES for SEEA Explorer" [37], the report "Monetary valuation of ecosystem services and ecosystem assets for ecosystem accounting" [35], etc.

There are also tools that support databases, including precalculated value estimates assigned not to specific solutions and best practices but to biomes, ecosystem services, terrestrial areas, etc. Such tools are the ARIES for SEEA [37] and the InVEST software [38].

The Environmental Monetization Tool of IDS4Clima supports the environmental monetization of solutions and best practices (cases). It is primarily based on the *System of Environmental Economic Accounting - Ecosystem Accounting 2021* (SEES-EA), in addition to *Environmental Accounting* (EA) and *Environmental Management Accounting* (EMA) frameworks.

The Environmental Monetization Tool of IDS4Clima (EMT-IDS4Clima) is based on a harmonizing approach by applying a coherent set of data that can support a variety of specific decision-making approaches, such as cost-benefit estimates, etc. For example, measures of expenditures for ecosystem restoration can be compared with changes in ecosystem status and changes in ecosystem service flows to support the evaluation of the effectiveness of each expenditure.

EMT-IDS4Clima supports the decision-making process for environmental costing. The user can enter or access a case from the Case Base in the specific format presented in Section 3.3, and EMT-IDS4Clima will determine the environmental costs. It will then calculate the existing impact of a business process on the environment, in monetary terms, using certain calculation methodologies.

EMT-IDS4Clima exploits a specific calculation methodology for each different attribute value of the field "improvement," which is based on various user-defined parameters. The adopted calculation methodologies are based on those included in the report "Monetary valuation of ecosystem services and ecosystem assets for ecosystem accounting" [35]. A publicly available folder (https://github.com/vutsinas/IDS4Clima) has been created, including an Excel file with the type of calculation methodology proposed for each different attribute value of the field "improvement." In the current version of EMT-IDS4Clima, only a small subset of these attribute values is covered.

4.1. An Example of Applying the Environmental Monetization Tool of IDS4Clima

To demonstrate the application of the Environmental Monetization Tool of IDS4Clima, consider the case with ID 043 (https://climate-adapt.eea.europa.eu/metadata/case-studies/building-fire-resilience-using-recycled-water-in-riba-roja-de-turia-spain) stored in the Case Base of IDS4Clima (https://github.com/vutsinas/IDS4Clima). The improvements achieved are "Reduced risk of fires" and "Water saving".

To the "Reduced risk of fires" value, a methodology is assigned based on "Replacement costs/Avoided damage/Directly observable values" that requires "Least cost alternative, Observable value" types of parameters (pages 38, 39, and 24) [36]). More specifically, since the construction of the resilience project presented in case 043 avoids the risk of fire, the total cost includes both the environmental cost and the suppression cost.

a. Suppression costs are costs that are recorded in the books of account and are available. By the benefit transfer method, and according to the National Interagency Fire Center [39], the suppression cost of wildfires was in 2023, 1.175,35$/acre or 1.065,00€/acre. Therefore, the necessary user-defined parameter is the area in acres. Based on the description of case 043, and converting the acres to hectares, the suppression cost is 350*1.065= 372.750,00 €.
b. Environmental cost consists of the cost of CO2 emissions from combustion [40], the cost of loss of CO2 capture capacity [29], and the cost of the effect of the urban forest on the value of real estate. In the publicly available folder (https://github.com/vutsinas/IDS4Clima), an analytical calculation of environmental cost [41, 42] is shown.

To the "Water saving" value is assigned a methodology based on "Directly observable values" that needs "Observable value" type of parameters [35]. According to "Water ranking in Europe 2020" [43], the average water price in 2020 was 3.50 €/m^3. Therefore, the required user-defined parameter is water volume in m^3. Based on the description of case 043, the cost is 80,000 m^3 * 3.50 € = 280,000.00 € per year.

5. Conclusion

The paper presents a Decision Support Tool for climate change and resilience pathways, which is the first, to our knowledge, that is based on a hybrid reasoner for supporting decision-makers. Such a hybrid reasoner is effective in reasoning about domains including both a limited set of general rules and extensive specific knowledge that can be formed as cases.

Moreover, a specific hybrid reasoner is used [5], which combines RBR, CBR, and Process Mining. Process Mining focuses on automatically generating a process model from event-based data (e.g., activities being executed) created and stored in information systems to extract knowledge and serve as a starting point for analyzing executed processes [44]. The Process Mining layer of the hybrid reasoner can be used to consider possible future facts, justified by the current ones.

The Process Mining layer of the hybrid reasoner of IDS4Clima is deactivated. However, in future work, we plan to apply this layer to the seven case attributes that represent the steps or stages identified during the implementation of project solutions. Thus, given a case and some implementation steps that have been followed, possible future successful implementation steps could be forecasted and then suggested by IDS4Clima to the decision-maker.

A prototype of the proposed Decision Support Tool is implemented, consisting of 100 cases and 48 rules. Moreover, in the prototype, only a small subset of attribute values of the field "improvement" is assigned a specific cost calculation methodology, which is exploited by EMT-IDS4Clima. Even for such covered attribute values of the field "improvement," the assigned cost calculation methodology is not exhaustive. For instance, in the example presented in 4.1, the following costs also stand out: 1) Cost due to soil erosion, such as from flooding; 2) Reduction of the water table, due to additional runoff, reduction of local rainfall, and pollution; 3) Destruction of biodiversity; 4) Loss of recreational areas; 5) Increase in diseases, especially zoonotic infectious diseases such as malaria, etc. However, this work aims at emphasizing the fact that the built-in calculation of environmental cost in monetary terms is essential to such a decision support tool and, also, at demonstrating how this calculation can be achieved while preserving comparability in the valuation process (see, e.g., [45].

In the future, we plan to set up a web-based application to allow interested users to add more cases to the Case Base of IDS4Clima. Moreover, we plan to turn the prototype into an integrated system.

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