



INNOVATING FOREST ECOSYSTEM MANAGEMENT WITH ADVANCED MULTI-CRITERIA DECISION-MAKING METHODS

MARCO HENRIQUE VIEIRA MARTO

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TESE ELABORADA PARA OBTENÇÃO DO GRAU DE DOUTOR EM ENGENHARIA
FLORESTAL E DOS RECURSOS NATURAIS

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CONTENTS

ACKNOWLEDGMENTS	xii
ABSTRACT	xiv
RESUMO	xv
RESUMO ALARGADO	xvi
PREAMBLE	xix
INTRODUCTION	1
ARTICLE 1: Web-Based Forest Resources Management Decision Support System.....	7
ARTICLE 2: A web-based approach for visualizing interactive decision maps.....	29
ARTICLE 3: Combining decision support approaches for optimizing the selection of bundles of ecosystem services	46
CONCLUSION.....	61
REFERENCES	64

INDEX OF FIGURES

Figure II.1. wSADfLOR architecture. Modules and information flows.....	13
Figure II.2. wGUI for displaying part of the study area as well as stand-level inventory data...	14
Figure II.3. wGUI for creating prescriptions and generating the decision space for the planning horizon.....	15
Figure II.4. Interactive decision maps for a decision problem. The x-axis represents the total wood (TOTTIMBesc; harvested wood, and thinned wood), and the y-axis represents the volume of ending inventory (Vol_Per9esc). On the scale, colors represent the five Pareto frontiers for five levels of average carbon sequestration (CTOTALesc).....	17
Figure II.5. Pareto frontier showing the trade-off between average carbon sequestration (10^5 Mg year ⁻¹ ; CTOTALesc) on y-axis and total wood-harvested wood and thinned wood (10^6 m ³ ; TOTTIMBesc) on the x-axis.....	19
Figure II.6. Pareto frontier showing the trade-off between the biodiversity indicator (IBiodiversity) on the y-axis and total wood-harvested and thinned volume (10^6 m ³ ; TOTTIMBesc) on the x-axis.....	19
Figure II.7. Interactive decision map showing the trade-off between three criteria: value of biodiversity indicator (ranges from 0 to 5 in its original scale; IBiodiversity) on the y-axis; total wood (10^6 m ³ ; TOTTIMBesc) on the x-axis, and volume of ending inventory-standing volume in last year of planning horizon (10^6 m ³ ; Vol_Per9esc) on the colored scale.....	20
Figure II.8. Interactive decision map showing the trade-off between three criteria: average carbon sequestration (10^5 Mg year ⁻¹ ; CTOTALesc) on the y-axis; volume of ending inventory-standing volume in last year of planning horizon (10^6 m ³ ; Vol_Per9esc) on the x-axis; and total wood (10^6 m ³ ; TOTTIMBesc) on the colored scale.....	21
Figure II.9. Questionnaire responses regarding the question regarding the easiness of use SADfLOR. Answers to each question were grouped into three categories: 1–3, 4, and 5–7, representing negative, neutral, and positive answers, respectively. NA represents not available (non-responses).....	22
Figure II.10. Questionnaire responses regarding the question on the usefulness of wSADfLOR. Answers to each question were grouped into three categories: 1–3, 4, and 5–7, representing negative, neutral, and positive answers, respectively. NA represents not available (non-responses).....	24

Figure III.1. Generation of Pareto frontiers from the Pareto hull. (a) Initial convex hull of feasible solutions (x_i, x_j) . (b) Edgeworth–Pareto hull in the criteria decision space (z_i, z_j) . (c) Set of efficient solutions in the criteria decision space (z_i, z_j) . (d) Extension to the Pareto frontier for the efficient solutions set considering two criteria (z_i, z_j) in order to simplify the representation. (e) Pareto frontiers representation considering three criteria (z_i, z_j, z_k)	34
Figure III.2. Communication client-server based on a Java Applet to show Pareto frontiers....	35
Figure III.3. Communication between client's device, PHP server and computation server ...	36
Figure III.4. Decision tool's flowchart.....	37
Figure III.5. Web graphical user interface (wgui) to choose the criteria to maximize or minimize, define any constraints on the criteria space (in this case $\text{totcrop} \leq 80\%$) and generate the Edgeworth–Pareto hull. This wgui shows the discrepancy between the convergence process and the real hull, the number of facets of the hull and the number of tops of the hull.....	38
Figure III.6. Representation of Pareto frontiers for the criteria totcrop (horizontal axis; in %), leveldrp (vertical axis; in %), and lakepol (represented by slices; in mg L^{-1}).....	39
Figure III.7. Representation of Pareto frontier with only one frontier (one color) with tradeoffs between totcrop (in %) and leveldrp (in mg L^{-1}) and the lakepol (in %) defined by the movement of the slider	39
Figure III.8. Wgui for choosing the criteria to be used in the construction of the Pareto-hull.....	40
Figure III.9. Interactive decision map showing the trade-off between four criteria: volume of ending inventory (10^6 m^3 ; Vol_Per9esc) in the y-axis; total wood (10^6 m^3 ; TOTTIMBesc) in the x-axis; the average carbon sequestered (Mg year^{-1} ; CTOTALesc) in the colored scale and the chosen level of net present value level (10^8 EUR ; NPV) in the slider ($0.64 \cdot 10^8 \text{ EUR}$).	40
Figure III.10. Interactive decision map showing the trade-off between four criteria: volume of ending inventory (10^6 m^3 ; Vol_Per9esc) in the y-axis; total wood (10^6 m^3 ; TOTTIMBesc) in the x-axis; the chosen level of average carbon sequestered (Mg year^{-1} ; CTOTALesc) in the first slider ($4.17 \text{ Mg year}^{-1}$) and the chosen level of net present value level (10^8 EUR ; NPV) in the second slider ($0.64 \cdot 10^8 \text{ EUR}$).....	41
Figure IV.1. Zona de Intervenção Florestal (ZIF) Paiva and Entre-Douro e Sousa. (a) location of the study area in Portugal; (b) classification of the study area into stands.....	50
Figure IV.2. Decision support flowchart.....	51

Figure IV.3. Trade-offs between three criteria. On the x-axis TOTTIMBesm total wood (10^6 m ³). In the y-axis, Vol_Per9esc, Volume of Ending Inventory (10^6 m ³). Each of the seven decision maps corresponds to a level of CTOTALesc, carbon sequestration (10^5 Mg year ⁻¹). The other criteria, net present value (10^8 €; NPV; on the first slider) and biodiversity indicator ([0, 5] (IBiodiversity; on the second slider) have been fixed at 0.63 and 1.61, respectively. Solutions A–F correspond to six alternative sets of criteria values.....	53
Figure IV.4. The Criterium Decision Plus (CDP) model to choose the best nondominated point from the Pareto frontier.....	54
Figure IV.5. Contributions of primary decision criteria (Figure 4) to the overall CDP utility score for the six solutions (A to F) from the Pareto frontier analysis (Figure 3).....	55
Figure IV.6. NetWeaver model to assess delivery of ecosystem services for individual stands. Data inputs at the stand level vary by Pareto solution (A–F), so this model is evaluated in EMDS with a separate assessment for each Pareto solution (Figure 7). Each oval represents a logic topic. Gray topics shown at the bottom of the diagram are elementary topics that evaluate data inputs with fuzzy membership functions.....	55
Figure IV.7. Evaluation of individual stands for solutions A to F from the Pareto frontier (Figure 3) with the values of variables per ha using the same NetWeaver model used for evaluating the best point (Figure 6). The percentile 90 was used as the maximum.....	56
Figure IV.8. Best solution (A to F from Pareto frontier) for each stand, based on NetWeaver scores for each solution from the NetWeaver model (Figure 7).....	57

INDEX OF TABLES

Table o.1. Articles that compose the thesis.....	xix
Table o.2. National and international projects that supported this Ph.D. thesis.....	xx
Table o.3. Other publications as co-author.	xx
Table o.4. Oral communications as first author.....	xxi
Table o.5. Oral communications as co-author.....	xxi
Table IV.6. Selected results for ecosystem services for the planning horizon of 90 years ^a for the Zonas de Intervenção Florestal Paiva and Entre-Douro e Sousa (ZIF_VS).....	53

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ABSTRACT

This work focuses on innovating forest ecosystem management planning and on enhancing its contribution to the provision of ecosystem services. A web-based forest decision support system was developed to support public and private forest managers, involving operational research methods. First, all work related to database management and the integration of data was carried out. Databases were created with PostgreSQL, which on the one hand facilitated the development of multi-criteria linear programs, and on the other met all the data and information needs of a forest decision support system, not only for data processing and information presentation, but also as a source to be consulted and analyzed by forest decision makers. The wSADfLOR, a forest web-based decision support system, integrates one analytic tool to visualize interactive decision maps showing the decision space and trade-offs among the criteria in Pareto frontiers, according to forest users' management options. Taking advantage of constant improvements in the Interactive Decision Maps tool in wSADfLOR, a second article was developed regarding a web-based approach to show interactive decision maps with Pareto frontiers. Based on these interactive decision maps and jointly with some decision support systems available in the EMDS platform (Criterion DecisionPlus and NetWeaver), a hybrid decision methodology for cases in which there is no consensus among the solutions chosen by different (groups of) forest decision makers was developed, enabling them to choose a unique strategic decision plan.

Keywords: decision support systems, multi-criteria analysis, Pareto frontier, web-based, forestry ecosystem management

RESUMO

Este trabalho enquadra-se no planeamento inovativo da gestão de ecossistemas florestais e na sua contribuição para a decisão da provisão de serviços de ecossistema. Procedeu-se ao desenvolvimento de um sistema de apoio à decisão para a web para apoiar os gestores florestais públicos e privados, envolvendo métodos de investigação operacional. Numa primeira fase houve a necessidade de fazer todo o trabalho de integração e gestão de bases de dados de diversas proveniências e temáticas. Sendo criadas bases de dados em PostgreSQL que permitiram, por um lado desenvolver os modelos de programação linear multicritério e por outro alimentar todas as necessidades de dados e informação inerentes a um sistema de apoio à decisão florestal, quer para processar dados ou mostrar informação de forma a poder ser consultada e analisada pelos decisores florestais. O wSADfLOR, sistema de apoio à decisão florestal baseado na web integra uma ferramenta analítica para a visualização de Mapas de Decisão Interativos mostrando o espaço de decisão e tradeoffs entre os critérios sob a forma de Fronteiras de Pareto, de acordo com as opções de gestão florestal dos utilizadores. Tirando partido do desenvolvimento constante da ferramenta de decisão incluída no wSADfLOR para mostrar mapas de decisão interativos, foi desenvolvido um artigo sobre uma abordagem para a construção de mapas de decisão interativos que incluem fronteiras de Pareto. Baseado nestes mapas de decisão interativos e conjuntamente com alguns dos sistemas de apoio à decisão disponibilizados na plataforma EMDS (Criterion DecisionPlus e NetWeaver), foi desenvolvida uma metodologia de decisão híbrida para os casos de não haver consenso nas soluções escolhidas pelos (grupos de) decisores florestais e deste modo apoiá-los na escolha de uma única decisão estratégica.

Palavras-chave: sistemas de apoio à decisão, análise multicritério, fronteiras de Pareto, baseado na web, gestão de ecossistemas florestais.

RESUMO ALARGADO

O principal objetivo deste trabalho prende-se com o desenvolvimento de sistemas de apoio à decisão e métodos de decisão inovadores baseados em otimização multicritério e computação para apoiar decisores públicos e privados na gestão e planeamento da oferta de serviços de ecossistema florestais, assim como recursos naturais.

Os sistemas de apoio à decisão (SAD) têm sido usados eficientemente em diversas áreas do conhecimento nas ciências do ambiente de modo a apoiar decisores nas suas atividades profissionais, nomeadamente em gestão e planeamento florestal, gestão de recursos naturais e ecologia da paisagem (Rammer et al. 2014; Kochilakis et al. 2016). De acordo com Holsapple 2003, o principal objetivo de um SAD é apoiar as atividades de tomada de decisão e geralmente é composto por um sistema de linguagem, um sistema de apresentação, um sistema de conhecimento e um sistema de processamento do problema.

Esta definição pode ser alargada aos sistemas baseados na web, disponibilizados por um browser, que funciona com a interface para pedidos e respostas entre cliente (que pode ser um computador, um *smartphone* ou um *tablet*) e um servidor web.

As páginas web dinâmicas são compostas por interfaces e formulários gráficos que têm evoluído na sua interatividade com o conceito web, permitindo a interação dos decisores com sistemas em tempo real levando ao fenómeno da gamificação (Deterding et al., 2011). Parte deste trabalho é dedicado a sistemas de apoio à decisão baseados na web para a apresentação de Mapas de Decisão Interativos (MDI) para apoiar gestores florestais e ambientais nas suas decisões.

Desde os anos 80 do século passado que têm sido desenvolvidos SAD para apoiar decisores e outros utilizadores na gestão de produtos e outros serviços de ecossistema florestais. Os SAD devem manter os estados e processos dos sistemas biofísicos em boas condições e ao mesmo tempo tentar satisfazer as necessidades de bens e serviços (Grumbine, 1994).

Para a sustentabilidade da gestão florestal é deveras importante fazer face às procura de serviços de ecossistemas sem pôr em causa a qualidade e renovação dos ecossistemas para gerações futuras (Maser, 1994).

O wSADfLOR, um SAD florestal e para a gestão dos recursos naturais desenhado para a web é apresentado e descrito no primeiro artigo deste trabalho. Este SAD concilia a) um sistema de informação para a gestão com um sistema de gestão de bases de dados (SGBD) em PostgreSQL para apoiar toda a arquitetura e um sistema de informação geográfica, com b) simuladores da dinâmica da vegetação, integrando o standsSIM (Barreiro et al., 2016), que simula prescrições ao nível da unidade de gestão, c) técnicas de otimização, métodos para mostrar mapas de decisão interativos para apoiar a análise e decisão multicritério (Lotov et al., 2004; Efremov and Lotov, 2014) e d) os formulários e interfaces baseados na web com rotinas de análise e reporte de informação para cabazes de serviços de ecossistema escolhidos como soluções consensuais pelos decisores ou utilizadores do sistema. Este SAD foi testado por um grupo de 18 utilizadores florestais e decisores num estudo aplicado a uma área de estudo real.

O segundo artigo é bastante relacionado com os dois anteriores e foca-se na abordagem para a construção de Mapas de Decisão Interativos (MDI) para representar a análise de tradeoffs

entre vários critérios nas fronteiras de Pareto disponibilizadas na web. Esta abordagem para a construção de invólucros convexos de Edgeworth-Pareto e Mapas de Decisão Interativos tira partido da evolução da capacidade de processamento e rapidez dos computadores e permite aos decisores desenvolver análises multicritério mais facilmente (Kitano, 2002).

Os problemas de ciências ambientais e de gestão florestal de serviços de ecossistema e produtos são bastante adequados para a aplicação destas técnicas, pois têm em conta geralmente critérios múltiplos (produtos e serviços) que competem no processo de otimização e podem representar tradeoffs nas fronteiras de Pareto.

Existem vários exemplos de estudos desenvolvidos nas ciências do ambiente e florestais onde se utiliza esta metodologia de análise multicritério, como Efremov et al. 2009, Dietrich et al. 2006, Lotov et. al 2013 e mais recentemente os estudos desenvolvidos em colaboração do Centro de Estudos Florestais (Universidade de Lisboa) com a Universidade de Évora (Borges et al., 2014a; Borges et al., 2017; Garcia-Gonzalo et al., 2015; Marques et al., 2017 and Marto et al., 2018). Nestes últimos trabalhos, a análise multicritério de fronteiras de Pareto foi desenvolvida usando uma implementação *Standalone*.

O presente trabalho apresenta uma nova abordagem que envolve uma implementação em PHP com uma arquitetura cliente-servidor, onde o servidor responde a pedidos do cliente que é um simples utilizador. Foram desenvolvidas anteriormente outras abordagens e metodologias para representar fronteiras de Pareto na web, como o trabalho de Tóth et al. 2010 (ECOSEL: an auction mechanism for forest ecosystem services).

O terceiro artigo deste trabalho envolve a fusão do wSADfLOR com alguns SAD disponíveis no EMDS (Ecosystem Management Decision Support). Surgiu como uma resposta ao problema de quando existem pelo menos dois decisores e estes não estão de acordo nas quantidades de serviços de ecossistema que devem constituir o cabaz final (uma única solução do problema). Por outras palavras, num caso geral, quando existem várias soluções não dominadas caracterizadas por constituírem as diferentes escolhas dos decisores.

O EMDS e os seus SAD, nomeadamente o NetWeaver e o Criterion DecisionPlus (CDP) podem ser usados para facilitar a negociação e o consenso (Borges et al., 2017). De facto, estes SAD multicritério podem comparar a performance de soluções alternativas múltiplas segundo um modelo pré-definido com os valores dos critérios resultantes do processo de otimização do wSADfLOR.

Todos os artigos foram desenvolvidos com o objetivo de apoiar os decisores, gestores, investigadores e interessados nos assuntos florestais em geral. A sua participação no processo de desenvolvimento dos sistemas e ferramentas de apoio à decisão é muito importante para o aperfeiçoamento das ferramentas e para a futura construção de ferramentas úteis e de fácil manejo para que possam satisfazer as suas necessidades de gestão florestal.

Nesse sentido procurou-se manter uma estreita ligação com os seus potenciais utilizadores através de reuniões de trabalho onde foram questionados acerca da usabilidade e facilidade de manejo das ferramentas.

O feedback foi positivo e permitiu-nos desenvolver e adaptar os nossos sistemas de apoio à decisão às realidades de gestão dos parceiros e gestores florestais. Nesses questionários foi detetada a necessidade de uma formação adequada acerca de fronteiras de Pareto que foi

prontamente ministrada por professores e investigadores junto dos potenciais utilizadores nas reuniões de trabalho seguintes.

O presente trabalho apresenta um sistema de apoio à decisão florestal baseado na Web modular (wSADfLOR). Os módulos que compõem o sistema de apoio à decisão são: o módulo de gestão de informação que suporta todas as necessidades de dados e informação de todo o sistema de apoio à decisão e incorpora um sistema de informação geográfico sobre a área de estudo; um módulo de simulação onde são definidas pelo utilizador as operações florestais a utilizar e seleccionadas as opções de planeamento e gestão para a simulação dos dados de inventário; um módulo de métodos de planeamento florestal onde são escolhidos os critérios utilizados na otimização multiobjectivo e gerado o respetivo modelo matemático; e finalmente o módulo de análise de dados, onde são escolhidas e analisados as soluções para o planeamento através de mapas de decisão interativos, tabelas, mapas da área de estudo e gráficos.

Tirando partido do desenvolvimento do módulo de métodos de planeamento florestal, é explicada uma abordagem para a construção de mapas de decisão interativos na web que incluem fronteiras de Pareto, onde é mais detalhado o conceito de desenvolvimento das fronteiras de Pareto apresentado neste trabalho.

Visto que nem sempre os (grupos de) decisores têm decisões consensuais, foi desenvolvido um sistema de apoio à decisão híbrido que combina o wSADfLOR com o CDP e o NetWeaver que são sistemas de apoio à decisão incluídos no EMDS. Numa primeira fase as diferentes soluções em discussão são ordenadas tendo em conta o modelo e os critérios utilizados no CDP, posteriormente as prescrições de todas as soluções são comparadas e avaliadas segundo os modelos desenvolvidos no NetWeaver e finalmente é escolhida para cada unidade de gestão a prescrição de entre todas as soluções com score mais alto no NetWeaver para gerir a unidade de gestão.

PREAMBLE

This thesis comprises a set of scientific articles, two of which have been published, while the others are currently in the process of being edited for submission or have already been submitted. The main subject encompasses decision methods, primarily innovative decision support systems to support decision makers' analysis in order to improve the management of forest ecosystem services. To this end, data and information from case study areas are required, although it is worth noting that the methodologies and techniques used in this work could easily be applied to other case study areas that need to be studied.

In the Introduction (Chapter I), the contextualization of each article constituting this thesis is described. The objective of the articles and the thesis in general are large addressed in here. Chapter I includes the state of the art and some motivations for the articles written, as well as the subjacent work developed. The articles included in this thesis as chapters are shown in Table 1 and have each been assigned a Roman numeral (II–IV).

Table o.1. Articles that compose the thesis

Article 1: Marto, M., Reynolds, K. M., Borges, J. G., Bushenkov, V. A., Marques, S., Marques, M., Barreiro, S., Botequim, B., & Tomé, M. (2019). Web-based forest resources management decision support system. *Forests*, 10(12), 1079. doi:10.3390/f10121079

Article 2: Marto, M.; Bushenkov, V.A.; Reynolds, K.M.; Borges, J.G.; Marques, S. (2021). A Web-Based Approach for Visualizing Interactive Decision Maps. *Information*, 12, 9. doi: 10.3390/info12010009

Article 3: Marto, M., Reynolds, K., Borges, J., Bushenkov, V., & Marques, S. (2018). Combining decision support approaches for optimizing the selection of bundles of ecosystem services. *Forests*, 9, 438. doi:10.3390/f9070438.

As the first author of these articles, I am primarily responsible for the entire work. I developed most of the experimental work, and was supervised and assisted by my co-authors in collecting and validating the data, writing, editing, and improving the manuscripts. Chapter VII represents the conclusion of this thesis.

The Portuguese Foundation for Science and Technology (FCT) funded and supported this work through grant SFRH/BD/108225/2015. Other research projects that supported the work were:

Table o.2. National and international projects that supported this Ph.D. thesis.

ALTERFOR: Alternative models and robust decision making for future forest management. The project involves twenty parties from nine countries and ten case study areas. It is funded by the European Union's Horizon 2020 research and innovation program (grant agreement no. 676754).

SuFoRun: An exchange project supported by a Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) within the H2020 work program (H2020-MSCA-RISE-2015). It is focused on forestry and climate change interactions, including the development of adaptive forest management tools. The consortium is built to include highly qualified research institutions in eight countries (Spain, Portugal, Finland, Sweden, Costa Rica, Chile, Brazil, and the United States) that share complementary interests in key scientific disciplines for the development of the forest sector.

MODFIRE: A multiple-criteria approach to integrate wildfire behavior in forest management planning. Funded by FCT/FEDER.

BioEcosys: LISBOA-01-0145-FEDER-030391 - PTDC/ASP-SIL/30391/2017. This project aims to bring together multidisciplinary, state-of-the-art knowledge on forest ecosystem models, forest ecosystem management planning methods, and non-market forest-services payment mechanisms in order to design tools that may help forest policy and decision makers address current challenges in the forest sector.

Table o.3. Other publications as co-author.

Marques, S., Marto, M., Bushenkov, V., McDill, M., & Borges, J. (2017). Addressing wildfire risk in forest management planning with multiple criteria decision making methods. *Sustainability*, 9(2), 298. <https://www.mdpi.com/2071-1050/9/2/298>

Nordström, E. M., Nieuwenhuis, M., Başkent, E.Z., et al. (2019). Forest decision support systems for the analysis of ecosystem services provisioning at the landscape scale under global climate and market change scenarios. *European Journal of Forest Research*, 138, 561–581. DOI:10.1007/s10342-019-01189-z

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Table o.4. Oral communications as first author

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Marto, M., Bushenkov, V. A., & Borges, J. G. (2019). *An approach for representing Pareto frontiers on the web*. XXVI Meeting of the Portuguese Association for Classification and Data Analysis (JOCLAD 2019), Polytechnic of Viseu, April 11–13, 2019. <https://repositorio-aberto.up.pt/bitstream/10216/123014/2/332666.pdf#page=51>

Table o.5. Oral communications as co-author

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McDill, M. E., Marques, S., Borges J. G., & Marto, M. (2017). Designing forest landscapes to reduce the risk of fire. *Proceedings of the 17th Symposium on System Analysis in Forest Resources, August 27–30, Seattle, Washington, U.S.A.* <http://depts.washington.edu/ssafr17/preliminary-program-schedule/>

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Marques, S., Bushenkov, V. A., Lotov, A., Borges, J. G., & Marto, M. (2019). A participatory forest management planning approach supported by multicriteria decision methods. *Proceedings of the 18th Symposium on System Analysis in Forest Resources, March 3–7, Puerto Varas, Chile*, p. 54. <http://www.ssafr2019.cl/13/en/program>

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Mesquita, M., Marques, S., Marques, M., Marto, M., Constantino, M., & Borges, J. G. (2019). *An approach to address road network design, machinery location and routing problems in forest management planning*. Livro de Resumos do XX Congresso da Associação Portuguesa de Investigação Operacional APDIO, July 22–24, Tomar, Portugal, p. 89–90.

This work focuses on developing innovative decision support systems and decision methods based on multi-criteria optimization and computation to support public and private decision makers in delivering forest ecosystem services and natural resource management. Several fields in the environmental sciences are efficiently using decision support systems (DSS) in order to support managers and decision makers in their professional activity, namely in forest management planning, natural resources management, and landscape ecology (Rammer et al., 2014; Kochilakis et al., 2016).

According to Holsapple (2003), the main purpose of a DSS is to support decision making activities. A DSS is generally composed of a language system, a presentation system, a knowledge system, and a problem-processing system. However, this definition may be adapted with the recent evolution of web-based systems that are available via a browser that works as the interface for requests and responses between a client using any kind of computer, smartphone or tablet and the server.

Especially since the 1980s, DSS have been developed to support forest decision makers and stakeholders managing products or forest ecosystem services. Ecosystem systems should maintain the states and processes of biophysical systems in good order, and at the same time try to satisfy society's needs for goods and services (Grumbine, 1994). For the sustainability of forest management, it is deemed important to address contemporary demands of ecosystem services without precluding the quality and renovation of ecosystems for future generations (Maser, 1994). Forest DSS are typically constituted of a database management system, a model-based management system, and a methods-based management system (Borges et al., 2014b).

Some DSS operate a greater amount of the database management system, such as AFFOREST (Hansen, 2002) and FORESTAR (Shao et al., 2003). AFFOREST was developed to build management plans, mostly in Sweden, Denmark, the Netherlands, and Belgium. It was implemented as an extension of ArcView™ 3.2 (Environmental Systems Research Institute, Redlands, CA), and is considered a spatial DSS. On the other hand, FORESTAR is more dedicated to the Asian region. It integrates interfaces with geospatial data and helps forest management decisions to be made through querying, displaying information, and conducting statistical analysis.

Concerning vegetation dynamic simulation and optimization, various DSS have been developed in Europe. Decision Support Dobrova (DSD; Lexer et al., 2005) was developed for Central Europe and encompasses (among other objectives) timber production management, nature conservation, and biodiversity. Landscape Management System (LMS; McCarter, 2001) was built to support forest management analysis and allow decision makers to develop forest inventory projections over time in the form of various tabular and graphic views. The SILVA approach was developed based on single-tree forest growth simulators (Pretzsch et al., 2002). Other relevant forest resource projection models and systems include the European Forest Information Scenario Model (EFISCEN; Nabuurs et al., 2000; Pussinen et al., 2001) and the standsIM forest simulator (Barreiro et al., 2016). The ForestGALES (Dunham et al., 2000) was developed in the United Kingdom and consists of a probability-based model considering the evaluation of the impact of windthrow events

on forest stands (Pyatt et al., 2001), as well as an assessment of tree species' sustainability and a site's yield potential using the site index concept.

Some examples of methods-based management systems can be mentioned, not least the Ecosystem Management Decision Support (EMDS) system (Reynolds et al., 2014), a platform that runs landscape-level analysis integrated in a geographic information system (GIS). In this work, ArcGIS and DSS modules were used: a) NetWeaver Developer, a fuzzy logic analysis module useful for evaluating and comparing different prescriptions, considering bundles of ecosystem services in strategic forest management; and b) Criterium DecisionPlus, for hierarchizing all the efficient solutions identified from Pareto frontiers, considering the bundles of ecosystem services provided in the planning horizon. Other examples of methods-based management systems also exist, such as the Northeast Decision Model (NED; Nute et al., 2004) for natural resource trade-off analysis in project-level planning, Woodstock™, a strategic model-building component of the Remsoft Spatial Planning System (based on Jamnick and Walters, 1993) for modeling solutions obtained by simulation or optimization, and the ETÇAP DSS, initially developed by Baskent et al. (2008) with the purpose of jointly optimizing timber production, non-wood products, and other ecosystem services. In North America, Seely et al. (2004) have developed a hierarchical DSS (UBC-FM) considering multi-criteria management, Damme et al. (2003) have described a DSS for management planning and monitoring purposes, and Ouhimmou et al. (2015) have built a system to support decision makers in the allocation of timber to mills within a multi-objective planning context. Forest ecosystem DSS have evolved with the needs and demands of stakeholders, and they are built to make transparent decisions under conflicting interests for the development and implementation of management strategies (Borges et al., 2014b; Borges et al., 2017; Kangas & Kangas, 2005; Marques et al., 2011, 2013; Martins & Borges, 2007; Mendoza & Prabhu, 2005).

Web technologies not only provide a very convenient way of delivering DSS due to lower maintenance costs, thanks to close to real-time solutions and being accessible in almost every place (Chichernea & Pop, 2014), but they also promote advances in forest decision making science, making advanced management techniques and methods available via web browsers to a larger sample of target stakeholders and forest decision makers. In the literature, there are examples of web-based DSS corresponding to a vector of decision tasks, concerning data, information management, simulation and optimization, sensitivity analysis, collaboration, decision implementation, and visualization (Kochilakis et al., 2016). The Timberland Decision Support System (TDSS) is an example of non-industrial private forest landowners developed by Kirilenko et al. (2007). Moreover, Wu et al. (2012) have developed a web-based DSS for analyzing timber harvesting costs and productivity in the Appalachian region of the southeastern United States, while Rammer et al. (2014) have built the Adaptive Forest Management (AFM) ToolBox for generating optimized management plans at the level of management units or landscapes.

Furthermore, Garcia-Gonzalo et al. (2015) have presented the desktop version of SADfLOR. In contrast to the desktop version, wSADfLOR includes a database management system (DBMS) in PostgreSQL that supports not only the information management module but also all the other modules needs of data. Moreover, in the previous version the GIS was developed with MapWinGIS,

and in wSADfLOR the geographic information was displayed with KML files in Google Maps and QGIS to improve system flexibility. In addition to the desktop version and other DSS, wSADfLOR includes the simulators for *Pinus pinaster* Ait, *Eucalyptus globulus* Labil, and chestnut. In order to define a strategic forest management plan, wSADfLOR implements a powerful web-based version of Interactive Decision Maps (IDM) to display Pareto frontiers and to help decision makers in determining the best solution considering the trade-offs among the criteria considered in the optimization process.

The wSADfLOR, a web-based forest and natural resources DSS, is introduced in the first article of this work. It comprises: a) an information management system with a relational database, including PostgreSQL as its DBMS to support the whole system, as well as GIS; b) vegetation dynamics simulators, integrating standsSIM (Barreiro et al., 2016), a forest simulator that enables the simulation of stand-level prescriptions; c) optimization techniques, displaying interactive decision maps to support multi-criteria decision analysis (Efremov & Lotov, 2014; Lotov et al., 2013); and d) dynamic webpages with data analysis and reporting routines associated with the bundles of ecosystem services chosen as the consensual solution by the decision maker (stakeholder or user in general). The dynamic webpages are composed by web graphic user interfaces (wGUI) and are facilitated by the evolution of the web, allowing decision makers to communicate with systems in real time, sometimes leading to the gamification phenomenon (Deterding et al., 2011). Part of this work is dedicated to DSS and approaches for representing web-based IDM to support foresters and environmental managers in their decisions. The EMDS and its DSS – namely NetWeaver and Criterion DecisionPlus (CDP) – can be used to facilitate negotiation and consensus building (Borges et al. 2017). In fact, these multi-criteria DSSs can compare the performance of multiple alternative solutions following a predefined model with criteria values resulting from an optimization process of wSADfLOR.

On one the hand, CDP – which implements the analytical hierarchy process (AHP; Saaty, 1994), the Simple Multi-Attribute Rating Technique (SMART; Kamenetzky, 1982), or their combination – represents a good solution for setting priorities, hierarchizing the solutions, explaining the derivation of conclusions, checking model robustness, and providing trade-off analyses. The criteria are weighted by several decision makers: in this particular case study we consider the number of solutions equal to the number of (group of) decision makers and, following evaluation by the predesigned CDP model, the alternatives (non-dominated solutions) are ordered by their decision scores as a prioritized ranking of alternatives by preference (Reynolds, 2005). On the other hand, NetWeaver is based on fuzzy logic networks and is well suited to choose from all the prescriptions followed by the proposed non-dominated solutions those that present the maximum score obtained for each management unit, according to the logic model developed.

A hybrid approach is used, combining the wSADfLOR (previously introduced in the first article) with some DSS components of EMDS to suggest optimal selections of alternative management combinations in the study area. First, the decision space and the criteria space of the management planning problem are generated using a spatially explicit multiple-criteria method within wSADfLOR. Second, the trade-offs between criteria are shown and analyzed in the form of Pareto

frontiers. As a result, the decision makers can choose their respective solutions. In most cases they do not agree on a unique solution, thus leading to the third step. In the first aspatial phase and the start of the third step, the CDP component of EMDS is used to evaluate the aggregated performance of selected points on the Pareto frontier for all case study area management units. Finally, the second component of EMDS – NetWeaver – is used to recommend specific prescriptions, specifically those that performed better in terms of model scores for each management unit.

The third article of this work involves the fusion of wSADfLOR with some DSS available in the well-known supra-mentioned platform dedicated to DSS, EMDS. It emerges as a response to the problem when there are at least two decision makers who do not agree on the amount that each ecosystem service is represented in the bundle by a unique solution, in other words in a general case where there are various non-dominated solutions characterized by multiple decision makers' choices.

In fact, the IDM technique for displaying the trade-off analysis in Pareto frontiers has proved to be a powerful tool in multi-criteria analysis and optimization in order to help decision makers to provide solutions to forest and environmental sciences. In cases where (groups of) decision makers do not agree on a unique solution, a hybrid methodology that considers the IDMs together with CDP and NetWeaver (available in EMDS) is introduced in this work to help.

All of these articles aim to facilitate decision makers' activity, whether they be forest managers, stakeholders or (regional or national) government actors. Various techniques for analyzing and solving the problems have been developed, such as: a) wSADfLOR DSS for ecosystem services management and multi-criteria analysis (Chapter II); b) an approach for representing Pareto frontiers in the web and analyzing trade-offs between ecosystem services (Chapter III); and c) hybrid systems with the inclusion of DSS from EMDS together with wSADfLOR recurring to AHP, SMART and fuzzy logic techniques, to find a consensual solution among several from different decision makers (Chapter IV).

ARTICLE 1: Web-Based Forest Resources Management Decision Support System.

Article

Web-Based Forest Resources Management Decision Support System

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Abstract: In this paper, we present a web-based decision support system (DSS)—wSADfLOR—to facilitate the access of stakeholders to tools that may contribute to enhancing forest management planning. The emphasis is on a web-based architecture and a web graphic user interface (wGUI) that may effectively support the analysis of trade-offs between ecosystem services in order to address participatory and sustainable forest management objectives. For that purpose, the wGUI provides remote access to a management information system, enabling users to analyze environmental and biometric data and topological information as well. Moreover, the wGUI provides remote access to forest simulators so that users may define and simulate prescriptions such as chronological sequences of management options and the corresponding forest ecosystem services outcomes. Remote access to management planning methods is further provided so that users may input their objectives and constraints. The wGUI delivers information about tradeoffs between ecosystem services in the form of decision maps so that users in different locations may negotiate bundles of ecosystem services as well as the plan needed to provide them. The multiple criteria programming routines provide proposals for management plans that may be assessed further, using geographical and alphanumeric information provided by the wGUI. Results for an application to a forested landscape extending to 14,388 ha are presented and discussed. This landscape provides several ecosystem services and the development of its management plan involves multiple stakeholders. Results show that the web-based architecture and the wGUI provide effective access for stakeholders to information about the forest management planning area and to decision support tools that may contribute to addressing complex multi-objective and multiple-decision-maker management planning contexts. They also highlight that the involvement and participation of stakeholders in the design of the web-based architecture contributes to assuring the quality and the usability of the system.

Keywords: web-based architecture; decision support system; forest management planning; multi-criteria methods; tradeoff analysis

1. Introduction

Decision support systems (DSS) are commonly used in several fields in the environmental sciences—including forestry, natural resource management, and landscape ecology [1]—and are very useful to support forest management planning [2]. A DSS is a computer-based system composed of a language system, presentation system, knowledge system, and problem-processing system whose collective purpose is the support of decision-making activities [3]. A web-based DSS is a software application that can be accessed by computer, smartphone, or tablet, and which is composed of dynamic web pages and web-based graphic user interfaces accessible through a browser [3]. The present study focuses on the architecture of a web-based decision support system for forestry and natural resources management.

DSS have been developed to support forest decision-makers and stakeholders, especially since the 1980s. Frequently, DSS are more focused on one of the three components of a knowledge system as defined in [4] and may encapsulate: a database management system (e.g., data on the forest concerned), a model-based management system (e.g., models for predicting growth and yield), and a methods-based management system (e.g., for calculating key statistics or a solver for optimizing a problem).

AFFOREST [5] and FORESTAR [6] are examples of DSSs more focused on the database management system. AFFOREST is essentially a spatial DSS implemented as an extension of ArcView™ 3.2 (Environmental Systems Research Institute, Redlands, CA, USA). Responsibility for the information and views set out in this article/publication lies entirely with the authors. The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service. It was built to address management planning problems in Sweden, Denmark, The Netherlands, and Belgium. In turn, FORESTAR encompasses several interfaces with geospatial data for the Asian region, allowing querying and displaying, statistical analysis, and decisions made concerning forest management.

The literature reports the development and use of several DSS to simulate vegetation dynamics and ecosystem states. DSD [7] was one of the first DSS developed for central Europe, covering a range of objectives, including timber production management, nature conservation, and biodiversity. Other examples include (a) the Landscape Management System [8] that provides forest inventory projections over time in the form of various tabular and graphic views for sustainable forest management analysis, (b) the SILVA system [9] which was developed based on single-tree forest-growth simulators, (c) the European Forest Information Scenario Model (EFISCEN) [10,11], a forest resource projection model, and (d) the standsIM forest simulator [12]. Other tools have been developed for more specific analysis such as ForestGALES [13], a probability-based model built for assessing the impact of windthrow events on forest stands [14], developed in the U.K. for assessing tree species sustainability and estimating the yield potential of a site using the site index concept.

The literature further reports the development and application of DSS to address multiple criteria management problems. The Ecosystem Management Decision Support system [15], which integrates a variety of other DSS modules (NetWeaver Developer (Rules of Thumb, Inc., Northeast, PA, USA), Criterium DecisionPlus (InfoHarvest, Inc., Seattle, WA, USA), GeNIe (BayesFusion, LLC, Pittsburgh, PA, USA), and VisiRule (Logic Programming Associates, LTD, Nottingham, UK)), is a system that provides spatial decision support for landscape-level analysis through logic and decision engines integrated in a geographic information system (GIS; e.g., ArcGIS, QGIS, MapWindow, and DotSpatial). The northeast decision model (NED,[16]) was developed for natural resource tradeoff analysis in project-level planning, including resource goals such as timber production, visual qualities, water quality and quantity, wildlife habitat, forest health, and ecology. Woodstock™, a strategic model-building component of the Remsoft Spatial Planning System (based on [17]) also fits this category, permitting modeling solutions that are obtained by simulation, optimization, or a combination of both. The ecosystem-based multiple-use forest management (ETCAP) DSS developed by [18] has evolved to consider joint optimization of timber production, non-wood products, and other ecosystem services [19] with an architecture that integrates data, models, and methods bases. Seely et al. 2004 [20] developed the UBC-FM, a hierarchical DSS for evaluating multicriteria

management options. Damme et al. 2003 in [21] described a DSS for forest management planning and monitoring, while [22] developed a system to support the selection of harvest areas and the allocation of timber to mills within a multiobjective planning context.

Contemporary DSS in forest management need to routinely consider multiple decision criteria and account for multiple stakeholders with conflicting interests, leading to the need for more flexible and versatile approaches to decision support [23]. At the same time, contemporary management planning emphasizes more active roles for stakeholders in participatory processes for making decisions, and for development of management strategies and their implementation [24,25]. As a result, stakeholder involvement is increasingly linked to the development and improvement of DSS [26–30].

Web technologies have emerged as tools for effectively addressing this context. They provide integrated platforms for designing, developing, and implementing DSS, and offer decision makers and stakeholders remote access to advanced planning techniques and methods via the Internet through web browsers [31]. Other benefits of these systems for decision makers are that there is no hardware cost for maintenance, instant access to software updates, small initial investment, and reduced risk [31].

Current web-based DSS address a wide range of decision tasks based on data, information management, simulation and optimization, sensitivity analysis, collaboration, decision implementation, and visualization [1]. Kirilenko et al. 2007 [32] built a system focused on decision support for non-industrial private forest landowners, the Timberland Decision Support System (TDSS). TDSS is essentially educational software based on a small number of input parameters, and encouraging informed forest management. Another web-based DSS for analyzing timber harvesting costs and productivity was developed by Wu et al. 2012 [33]. This system combines a VB.NET platform and a MS SQL server as a database management system (DBMS), enabling the simulation of harvesting scenarios in the Appalachian region of the southeastern US. FLIRE is an example of a web-based DSS that allows planning services, operations, and management, considering flood and wildfire events [1]. The Adaptive Forest Management (AFM) ToolBox is a web-based system that encapsulates a database, vulnerability assessment tools, and an optimization tool to generate optimized management plans at the level of management units or landscapes [2]. Garcia-Gonzalo et al. [34] presented the desktop version of the SADfLOR DSS for evaluating tradeoffs between ecosystem services. Relative to the former desktop version, wSADfLOR introduces a variety of system architecture innovations to support a web-based DSS solution. First, wSADfLOR was implemented with a Database Management System (DBMS) in PostgreSQL, which makes access to data more efficient than the desktop version, and provides improved performance for the queries and procedures needed to support the calculations to display results in the Geographic Information System (GIS). Second, whereas the desktop SADfLOR implemented MapWinGIS as its GIS component, wSADfLOR uses KML files built in Google Maps and QGIS to support a web implementation to improve system flexibility. Third, while the previous system included growth and yield simulators for cork and holm oak, wSADfLOR also considers growth and yield simulation for *Pinus pinaster* Ait, *Eucalyptus globulus* Labil, and chestnut. Finally, wSADfLOR includes a powerful, web-based version of Interactive Decision Maps with dynamic graphical user interfaces to develop the tradeoff decision analysis with Pareto frontiers.

Nevertheless, no DSS has been developed thus far that takes advantage of the integrated functionality of databases, vegetation dynamics simulators, optimization techniques, methods to interactively display tradeoffs between ecosystem services, and web-based graphical user interfaces. This research targets the integration of these functionalities in order to increase the efficiency and the effectiveness of forest management planning. They are integrated within web-based SADfLOR (hereafter, wSADfLOR for brevity), a Portuguese web-based DSS, composed of (1) an information management system with a relational database having PostgreSQL as its DBMS to support the whole system and with a GIS submodule to allow the display of geographic information; (2) standsSIM [12], a forest simulator that allows the simulation of stand-level prescriptions; (3) a multi-criteria optimization and decision module that incorporates interactive decision maps [35,36] with a Pareto Frontier tool [29,34]; (4) an analytic module for reporting solutions and results; and (5) a web-based graphical user interface (wGUI) that provides decision makers and stakeholders with remote access to data, information, models, methods, and reporting routines encapsulated in wSADfLOR modules.

After describing the DSS, the system functionality is demonstrated by application to a forested landscape extending to 14,388 ha. The emphasis is on the assessment of the web-based functionality to analyze tradeoffs between ecosystem services by several decision-makers and stakeholders, who subsequently evaluated their experience in a questionnaire about wSADfLOR. In this application, users can select combinations of criteria to optimize: wood forest products (e.g., wood, volume of ending inventory), and ecosystem services such as carbon sequestration and biodiversity [37]. These criteria reflect the trends in forestry and natural resources [38–40] that broaden the scope of forest management by taking into account a wider range of ecosystem services.

2. Materials and Methods

2.1. Study Area

The forested landscape is located in a rural area in northwestern Portugal. It is characterized by numerous small private holdings. To solve the problem of forest management in such a landownership structure, several actions have been taking place in order to promote joint management over the past several years. Among those, the “Zonas de Intervenção Florestal” (ZIF) are areas that group small private owners around a common management plan. The study covers two ZIF areas, Paiva and Entre-Douro e Sousa (here designated as ZIF_VS). It is composed of 1976 stands and occupies an area of 14,388 ha. The dominant species is eucalypt (mostly *Eucalyptus globulus* Labil). Pure eucalypt stands extend over 66% of the area. There are mixed stands of eucalypt and maritime pine (*Pinus pinaster* Ait.) as well (33% of the ZIF_VS area). Hardwood species represent about 1% of the stands and are mostly chestnuts. The cooperation among owners is key to addressing landscape-level objectives such as the reduction of wildfire risk. Nevertheless, the challenge to developing a joint management plan calls for tools that may provide and distribute information about alternative courses of action and help owners and other stakeholders negotiate solutions.

2.2. Stakeholder Involvement in wSADfLOR Development

ZIF Paiva stands belong to 185 associated landowners while ZIF Entre-Douro e Sousa has 191 associated landowners. A local forest owners association is responsible for the development of its joint management plan. A group of 18 stakeholders—seven land owners, six forest managers, two administrators, two consultants, and one researcher—, was selected with the support of this association to participate in a workshop to demonstrate the functionality of wSADfLOR, to assess its usefulness and ease of use and to get input to enhance the system. Sixteen stakeholders had more than four years of experience in the forestry sector, 10 had participated in more than three research and development projects, and 7 had used DSSs more than three times. The workshop was co organized by the forest owners association and the research team and it involved four facilitators. The latter had expertise and experience of developing and applying forests management decision support tools. The workshop took place in a room as this facilitated the communication of information between stakeholders in order to address the workshop objectives. The workshop started

with an introduction to the system and its main components. This was followed by a session when stakeholders had the opportunity to work with it. They tested all the functionalities of wSADfLOR and used all the modules from the visualization of the management area to the data analysis of the results with the support of the researchers when necessary. Afterwards, all 18 stakeholders answered the assessment questionnaire. The objective of the questionnaire was to learn how this group of stakeholders perceived the user-friendliness and utility of wSADfLOR. Stakeholders were asked to respond to survey questions using a 7-point Likert scale. For summarizing the survey results, answers to each question were grouped into three categories: 1–3, 4, and 5–7, representing negative, neutral, and positive answers, respectively. The involvement of the stakeholders has been deemed relevant for the evolution of wSADfLOR. Suggestions from stakeholders were considered over the course of the development process.

2.3. The Strategic (i.e., Long-Term) Forest Management Planning Problem

In order to test and demonstrate wSADfLOR, we consider the ZIF_VS landscape-level management planning problem. Its temporal horizon extends over nine 10-year planning periods. The simulation of stand-level prescriptions considers management options (e.g., range of rotation ages, species conversion options, fuel-treatment scheduling options) considered by stakeholders [29]. The set of ecosystem services to be provided by ZIF_VS was defined by stakeholders, and it includes eucalypt pulpwood and maritime pine sawlogs as well as hardwood sawlogs (mostly chestnut), carbon storage, and biodiversity. In this management planning problem, wSADfLOR is used to help stakeholders explore the criteria and decision spaces, namely through the presentation of tradeoff information on ecosystem services. In turn, stakeholders provide input regarding the easy of use as well as the usefulness of wSADfLOR to support that exploration and the solution of the forest-management planning problem. A questionnaire was designed for that purpose.

2.4. Web-Based DSS wSADfLOR's Structure and Modules

The wSADfLOR architecture (Figure 1) builds from PC-based versions of the DSS [34,41,42] to develop a web-based functionality that provides remote access to forestry data and information, to forest models, and to management planning methods. The emphasis is on an architecture that facilitates participation of stakeholders in the analysis of trade-offs between ecosystem services and in the negotiation of forest management plans. The Diagram of Activities of wSADfLOR (Figure 1) highlights the functionalities and the main relationships between the system components. They were implemented using PHP version 5 and JavaScript version ECMAScript 2015 and are described in the following subsections.

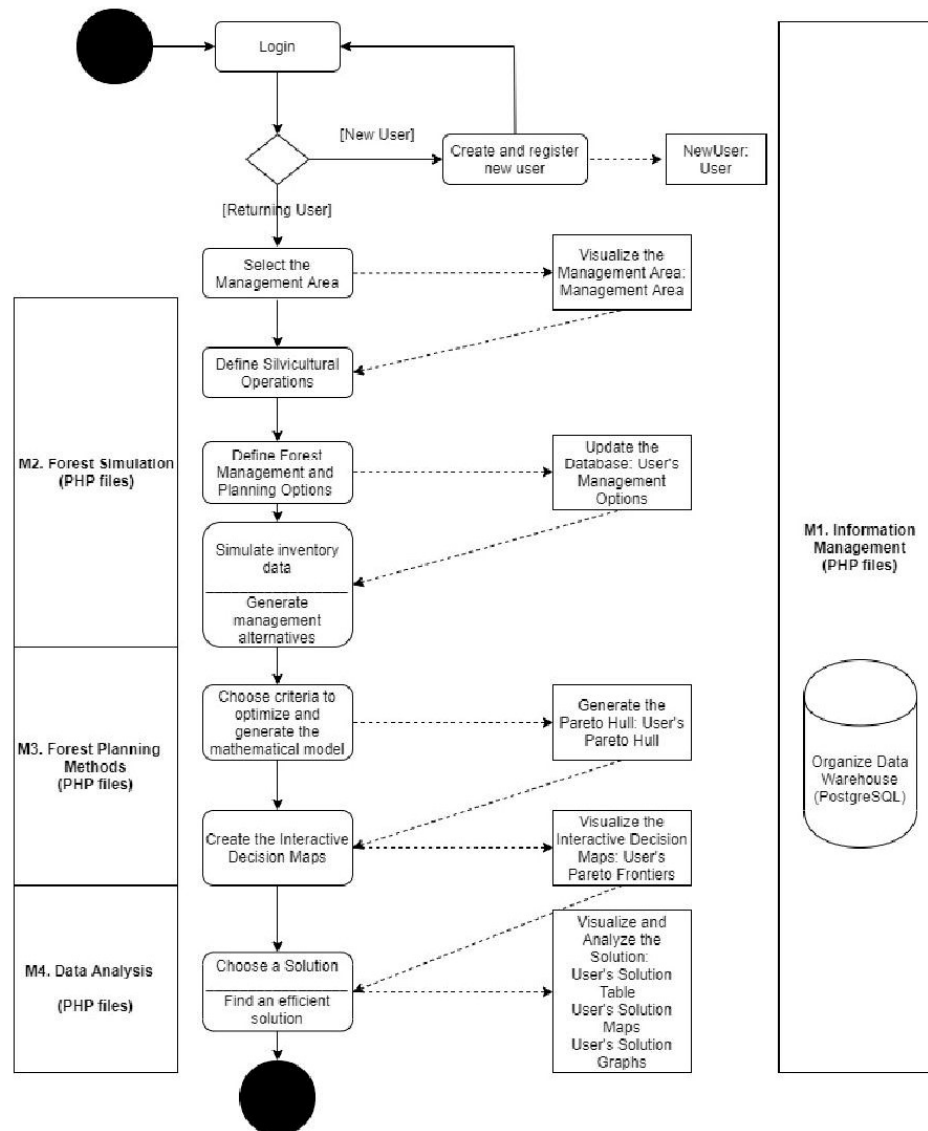


Figure 1. wSADfLOR architecture. Modules and information flows.

2.4.1. Information Management Module

The information management module (wIMM) in wSADfLOR includes a database and PostgreSQL procedures to provide all the data management needs of the system. It includes the routines for the authentication of login data and for delivering all data and information to the other modules. It currently stores and organizes data from 2130 forest inventory plots (339 maritime pine, 1723 eucalypt, and 68 hardwood (mostly chestnut) trees), in the ZIF_VS management planning area. It also stores forest operations data (e.g., labor and other resource requirements to implement management options and the corresponding cost) and prices.

Basic spatial attributes and neighborhood relations of the 1976 stands have to be taken into account when building a strategic forest plan intended for use by landowners. Therefore, the information management module includes a GIS component to provide accurate, precise, and

relevant information to decision makers for correct perception and interpretation of the main characteristics of the forests, and consequently of the results of the strategic plan when displayed in maps.

The data and information in the wIMM are accessed through various wGUI forms (Figure 2 shows an example form) that trigger the retrieval of data and information and its display in maps, graphs, or tables. The wGUI was developed with Keyhole Markup Language (KML) stand files in Google Maps. KML files for stands were created with the QGIS qgis2web plugin and the Google Fusion Tables application. The latter allows users to upload tabular data files (spreadsheets, CSV, and KML). KML stand files use a tag-based structure nested within elements and attributes based on the XML (Extensible Markup Language) standard. This format is useful to show geographic information in Google Maps applications. The wGUI uses these applications to display relevant stand information in various ways (e.g., charts, maps, and timelines).

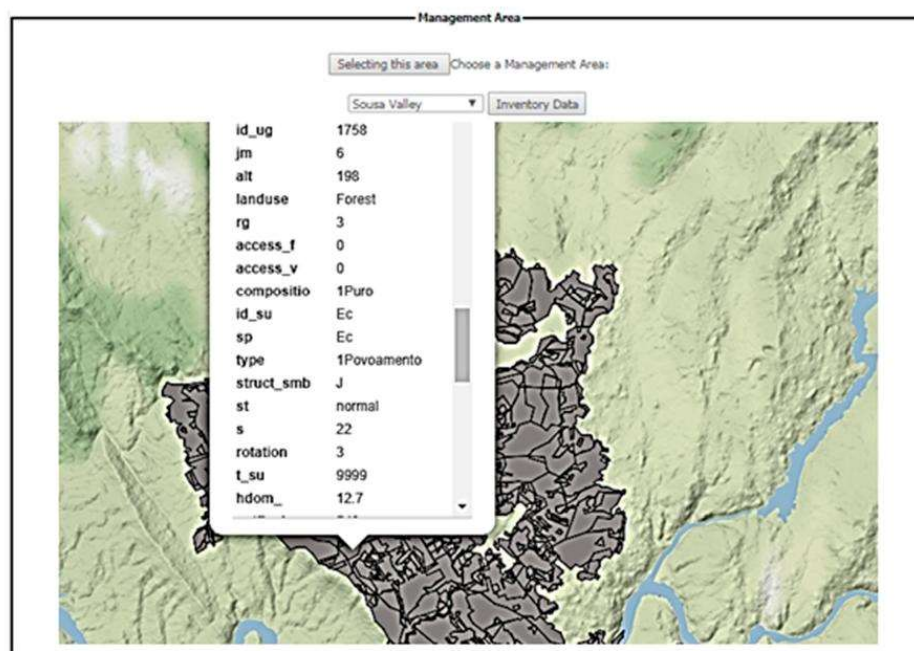


Figure 2. wGUI form displaying part of the study area as well as stand level inventory data.

2.4.2. Forest Simulation Module

The wSADfLOR forest simulation module (wFSM) encapsulates growth and yield models in standalone executable simulation files, whose outputs are included in the data warehouse and interact with the PHP programmed files. It is used to define silviculture models and to generate management alternatives (Figure 1). The standsSIM simulator [12] is useful to project stand growth and estimate wood product yields and carbon storage values. It also encapsulates models to estimate the value of stand-level biodiversity [37] and wildfire resistance indicators [43,44]. It simulates stand development under alternative stand-level prescriptions-sequences of silvicultural operations-according to management options specified by the user. The wGUI includes forms developed in PHP language for the user to trigger the generation of stand-level prescriptions over the planning horizon by inputting thinning regime options, rotation ages, species conversion, and fuel-treatment scheduling options as well as the extent of the planning horizon (Figure 3). In Figure 3, we only consider management alternatives for *Eucalyptus globulus*, Maritime pine, and Chestnut, because these are the most representative species for our case study area, but the wGui is easily configured for other species landowners might want to consider. The example below shows the instructions to

generate a set of prescriptions for maritime pine, combining thinning and clear-felling ages (e.g., 40, 45, 50, ... 60). In this example, the wFSM assumes that the last thinning occurs 5 years before the rotation age if the latter is less than or equal to 55 years. Moreover, the wFSM reads from the wIMM information about the stands where a species conversion (pine to chestnut) may take place. Finally, in this example, the user may specify a single fuel-treatment schedule to be applied over the whole planning horizon.

The screenshot shows a web-based user interface titled "Instructions for Generating Management Alternatives". It includes a "Save File(s)" button at the top. The interface is divided into several sections for configuring forest management parameters:

- High Forest - Maritime pine:**
 - Rotation: Minimum 40, Maximum 60, Step 5
 - Thinning: First 20, Last 55, Step 5
- High Forest - Chestnut:**
 - Rotation: Minimum 40, Maximum 70, Step 5
 - Thinning: First 15, Last 55, Step 5
- Coppice - Eucalyptus:**
 - Cycle: Minimum 10, Maximum 14
 - Rotation: 2 Cycles (selected), 3 Cycles
- Species Conversions:**
 - Initial Year: 2017, Final Year: 2043
 - ☐ Maritime pine to Chestnut
- Fuel treatment:**
 - ☐ No fuel treatment
 - ☐ Every 5 years
 - ☐ Every 15 years
 - ☐ Every year
 - ☐ Every 10 years

Figure 3. wGUI for creating prescriptions and generating the decision space for the planning horizon.

The wFSM is also used to generate the resource capability models (RCMs) [45] for the forest ecosystem management planning problems. The former consists of sets of mathematical equations in which prescriptions correspond to the decision variables. The coefficients of the decision variables in each equation describe the contribution of each prescription to the provision of each ecosystem service—namely pine wood, eucalypt pulpwood, chestnut sawlogs, volume of the ending inventory, carbon sequestration, wildfire resistance, and biodiversity—in each period of the planning horizon. Thus, the RCMs correspond to the decision spaces of planning problems for forest ecosystem management. These decision spaces are generated according to the silviculture options selected on the wGUI (Figure 3). Its input by the user triggers a call to functions in PostgreSQL as well as to functions coded in PHP in order to generate the full set of equations that describe the decision space. This set of equations is stored in a LP-format (extension for linear programming) file. The linear programming (LP) model is built according to the choices of the decision maker, considering whatever ecosystem services are of interest, and includes a set of equations, one for each management unit, which guarantees that only one prescription is applied to manage a polygon.

2.4.3. Forest Planning Methods Module

This module (wFPM) was developed mainly with HTML, JavaScript and PHP software. It reads the decision-space file written by the wFSM. The decision-space file and the coefficients of decision variables were previously calculated in wFSM or generated with some routines in PHP and PostgreSQL using data from wFSM. It also reads information provided by the user through the wGUI to define the set of management planning criteria and the policy model (Figure 4), which prescribes a set of management operations and policies for managing forest stands. This information is processed by PHP routines in order to develop the equations of the mathematical model (Figure 1). In this application of the system, the set of criteria includes eucalypt pulpwood, maritime pine sawlogs, chestnut sawlogs, carbon storage, biodiversity, wildfire resistance, volume of the ending inventory, and net present value. The latter may include conditions regarding product and revenue flows or the fluctuation over the temporal horizon of any indicator of an ecosystem service.

This information is translated by the wFPM into an input file that can be read by several off-the-shelf mathematical programming (e.g., linear programming, goal programming, mixed integer programming) routines and software (e.g., CPLEX or GLPK). GLPK was included as it is freeware that may be used to solve simple problems. The structure and contents of this linear programming (.lp) file were defined so that it may also be read by a set of Pareto frontier method routines to provide information about criteria tradeoffs. The reader is referred to [28] for a description of the mathematical approach to generate the feasible set in the criteria space. In this DSS, this set is built by an iterative procedure developed in C++, which runs as a standalone executable application. The wGUI enables the user to input constraints with respect to minimum and maximum criteria values for the planning horizon. The set of routines includes linear programming solvers to address the series of auxiliary optimization problems needed to develop the Pareto frontier method. They also include a PHP implementation of the Gift Wrapping Algorithm for building Convex Hulls [46] to generate decision maps. The wGUI enables the user to define the accuracy of the development of the decision maps and the corresponding Pareto frontiers. These are displayed by the wGUI (Figure 4) so that users can interactively analyze tradeoffs between up to five criteria. Users can use this information to select bundles of ecosystem services by clicking on a point in the Pareto frontier in the wGUI (Figure 4). The system is capable of displaying different projections, fixing some of the criteria. Each decision map displays tradeoffs between two criteria when up to three other criteria are fixed. Each map in a two-dimensional graph corresponds to a value of the third criterion. The system provides the user with sliders to change the values of a fourth and fifth criterion. When moving the slider(s) the decision maps in the two-dimensional graph change. For clarity, we chose to display only up to a maximum of three criteria our examples. This triggers the implementation of mathematical programming routines to report the corresponding forest ecosystem management plan. The results, with the strategic plan for each management unit, are shown in a CPLEX xml format or simply in a .csv flat file, representing all basic variables of the last optimization iteration. The reader is referred to [28,36] for a detailed mathematical description of the Pareto frontier method.

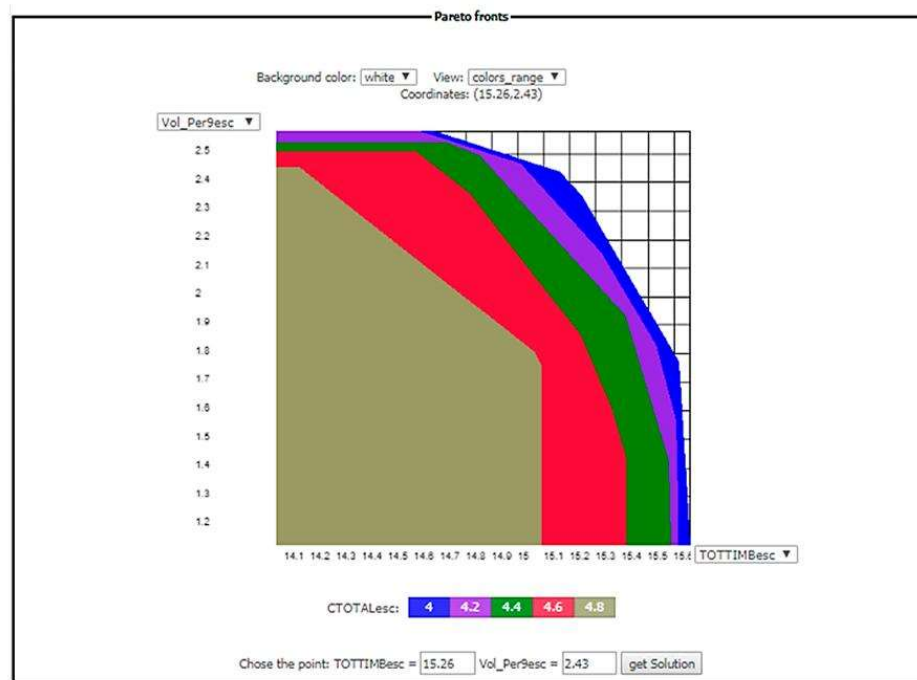


Figure 4. Interactive decision maps for a decision problem. The x -axis presents the total wood (TOTIMBesc; harvested wood, and thinned wood), and the y -axis represents the volume of ending inventory (Vol_Per9esc), and on the scale colors represent the five Pareto frontiers for five levels of average carbon sequestration (CTOTALesc).

2.4.4. Data Analysis

The data analysis module provides information about the bundles of ecosystem services selected by the user and the corresponding management plans. This information is displayed by the wGUI in the form of maps (KML files), tables, and charts (Figure 1). The wGUI can display information about the set of forest operations as well as about its stand and landscape-level outcomes in any given period of the planning horizon. Outcomes can also be aggregated for the whole planning horizon. The wSADfLOR's data analysis module complements the tabular results with a map showing the harvested and thinned volume in each 10-year period of the planning horizon. Additionally, a map with the annual distribution of these volumes per age class and species can be presented for each stand. In these dynamic graphical interfaces, the final harvest and thinned volume flows—as well as the carbon sequestered—can also be seen per period of the planning horizon. Finally, a graph with the distribution of standing volume along the planning horizon can also be presented.

3. Results

The decision maker starts their navigation in wSADfLOR with the authentication step. Once authenticated, they can visualize the case study area (ZIF_VS) and analyze some of the characteristics of the management area regarding the initial inventory available for each management unit in the GIS. After that, they decide which silvicultural operations will be chosen to best follow their aims. Because they have done this work, the simulation process will be developed. At the end of the simulation process, the system provides the data structured for building the mathematical model. The mathematical model is built according to the management decisions and criteria chosen by the end user. The Pareto Convex Hull is built by the system in the next step, and finally the interactive decision maps with the Pareto Frontiers are shown. At this point, the decision maker is ready to

choose the point which represents their preferences, taking into account the trade-offs (how much we need to sacrifice in the amount of one criterion for increasing the amount of another criterion) and then the optimization process generates the forest management plan. There are also some additional tabular, statistical, and graphical analyses shown, which are related to the plan that has been selected to manage the study area.

3.1. Simulation

In this application, the wFSM was used to generate stand-level prescriptions over a 90-year planning horizon with nine 10-year planning periods. The reader is referred to [29] for more details regarding the selection of management options to generate prescriptions in the ZIF_VS area. The latter are classified into four forest management models—mixed pine and eucalypt with pine as the dominant species (FMM1), mixed pine and eucalypt with eucalypt as the dominant species (FMM2), pure chestnut (FMM3), and pure eucalypt (FMM4). The decision space thus included 59,133 decision variables. Its linear programming formulation encompassed 1976 stand area equations and 46 equations to estimate the landscape-level provision of each ecosystem service over the planning horizon.

3.2. The Decision Support Process

The web version of decision maps developed in wSADfLOR is one important decision tool in this web-based system, and permits several analyses among the criteria to be considered in the optimization process. First, we analyze a trade-off with two criteria to be drawn on an interactive decision map (Pareto frontiers in Figures 5 and 6). Trade-offs were analyzed between average carbon sequestration ($10^5 \text{ Mg year}^{-1}$; CTOTALesc) and total wood (10^6 m^3 ; TOTTIMBesc) on one hand (Figure 5), and on the other hand between the biodiversity indicator (IBiodiversity) and total wood (10^6 m^3) (Figure 6). In both cases, the opportunity cost to have a greater amount of one criterion is reflected in a lower amount of the other scaled criterion on the efficient frontier of each polygon (considering we are maximizing the two criteria). All the criteria must have similar scales of magnitude to permit a good visualization with Pareto Frontiers, and to make the optimization process more efficient. Therefore, criteria were scaled as necessary. A performance runtime test for all modules of wSADfLOR was done. Running the information management module, namely to display the map with the management area and retrieve stand inventory, takes about 2 min. It takes about 3 min to run activities in forest simulation (using the information available by default). In the case of the forest planning methods module, the running time extends over about 4 min (from which about 2 min correspond to the construction of the Edgeworth-Pareto hull with three criteria). Finally, running the data analysis module takes about 6 min (including about 2 min to show the solution with the management plan). Nevertheless, the computational cost of a specific application will depend on the number of solutions t (e.g., points in the Pareto frontier) that the stakeholders may want to check.

3.3. Interactive Decision Maps in wSADfLOR

The polygon in Figure 6 is closer to the form of a triangle, while the polygon in Figure 5 has four vertices. The biodiversity indicator is a function of species and age, and there is a linear trade-off between total wood and the biodiversity indicator and a small variation of the biodiversity indicator as well. On the other hand, the trade-off in Figure 5 can be easily explained by the correlation between total wood and harvesting, because less trees means less capacity of the ecosystem to sequester carbon. Again in Figure 5, the trade-off is divided into two straight segments; in the segment on the left, if we want to change the amount of total wood from $15 \times 10^6 \text{ m}^3$ to $15.2 \times 10^6 \text{ m}^3$ (about 1.3%), the amount of average carbon sequestration will change from $4.8 \times 10^5 \text{ Mg year}^{-1}$ to $4.7 \times 10^5 \text{ Mg year}^{-1}$ (about 2%), whereas in the segment on the right, if we want to change from $15.5 \times 10^6 \text{ m}^3$ to $15.6 \times 10^6 \text{ m}^3$ (about 0.6%), the amount of average carbon sequestration will decrease about 6.8% (from $4.4 \times 10^5 \text{ Mg year}^{-1}$ to $4.1 \times 10^5 \text{ Mg year}^{-1}$). As a result, the slope in the first straight segment is about -0.5 whereas the slope in the right segment is about -3 . The common point to the two straight segments

is approximately the point (total wood, average carbon sequestration) = $(15.42 \times 10^6 \text{ m}^3, 4.61 \times 10^5 \text{ Mg year}^{-1})$.

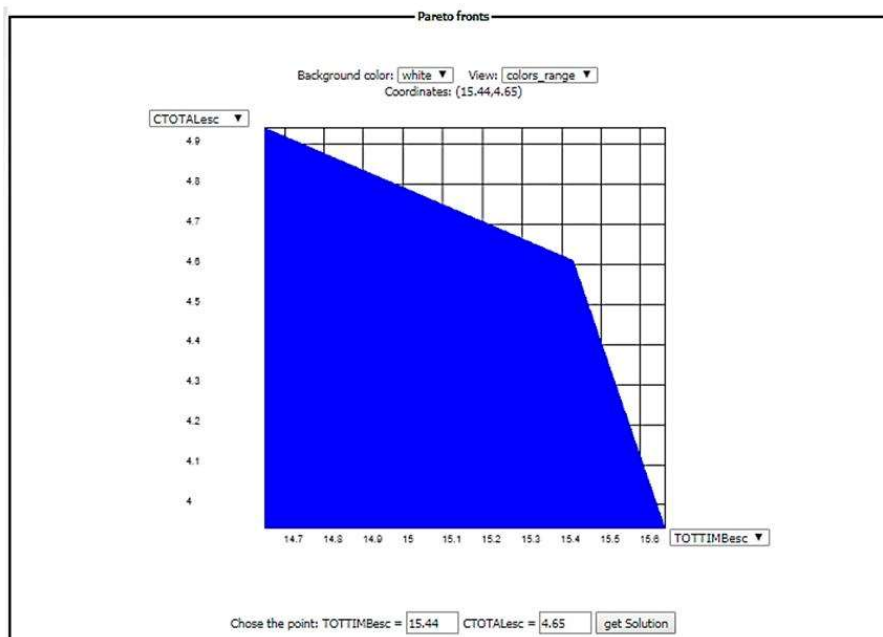


Figure 5. Pareto frontier showing the trade-off between average carbon sequestration (105 Mg year^{-1} ; CTOTALesc) in y -axis and total wood—harvested wood and thinned wood (106 m^3 ; TOTTIMBesc)—in the x -axis.

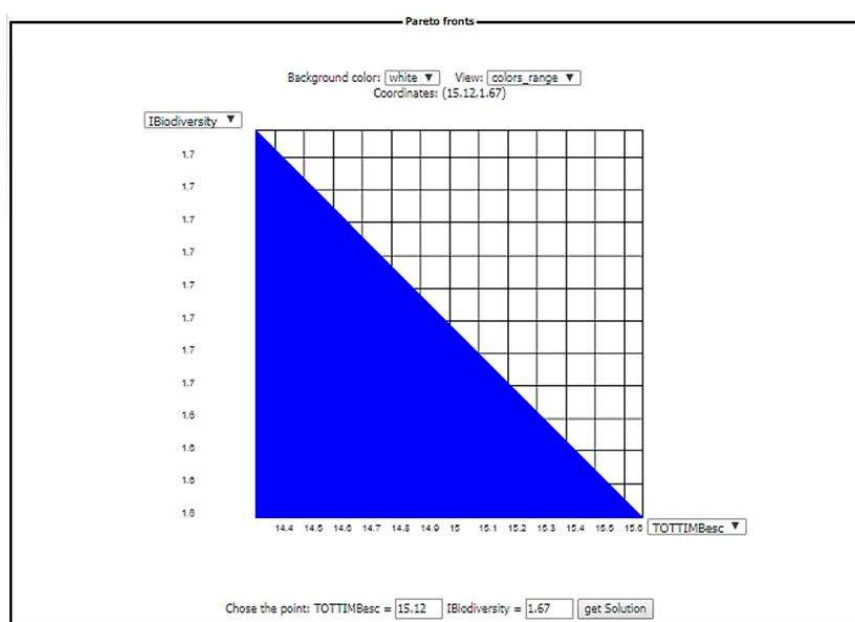


Figure 6. Pareto frontier showing the trade-off between the biodiversity indicator (IBiodiversity) in the y -axis and total wood—total harvested and thinned volume (106 m^3 ; TOTTIMBesc)—in the x -axis.

Next, the analysis is extended to a third criterion (Figures 7 and 8). The volume of ending inventory—the standing volume in last year of planning horizon (10^6 m^3 ; Vol_Per9esc) was introduced together with total wood and average carbon sequestration (Figure 8). In Figure 7, the third criterion is represented by colored slices indicating different discrete values, which are shown at the bottom of the decision map. Because all criteria are maximized at the same time, the interpretation of the sets of non-dominated solutions is very similar to the one for the previous two criteria (Figures 5 and 6). It is easy to find that the third criterion represented by the scale of colors increases as we are closer to the point with the lowest values for the criteria represented on the axis of each decision map because we are maximizing all the criteria. The non-dominated solutions represented in Figure 7 are on the three straight segments with absolute value of slope greater than 0 and smaller than infinite (inside the ellipse), whereas in Figure 8 it is more difficult to show all the non-dominated sets of solutions. We can find them when selecting all the straight segments for each Pareto frontier that do not belong to the set of vertical or horizontal straight segments that are borders of each slice on the decision map. Some interesting trade-offs are shown in Figure 7 between the three criteria involved, where we can conclude that if we want to choose a greater level for the biodiversity indicator in the ellipse for each fixed level of standing volume in the last year of planning horizon, then we need to decrease the level of total wood. This fact occurs due to a positive correlation of the biodiversity indicator with the age of the trees and species. Then, to get a higher level of total wood, we need to decrease the biodiversity indicator, and for lower levels of total wood we have higher levels of biodiversity and standing volume in the last year of planning horizon. The slope of the three straight segments that are the efficient solutions are the same because they are parallel. So, considering the criteria on the x -axis and y -axis, the amount we need to sacrifice to have a greater amount of the other criterion does not change for different values of the criterion represented by different colors for different values. Relative to Figure 8, we chose only three slices to be represented. For the minimum level of total wood ($14.5 \times 10^6 \text{ m}^3$) that is represented, the slope changes for each efficient straight segment represented as the Pareto frontier (all straight segments which are not vertical neither horizontal). For example, if we increase the volume of ending inventory from $2.2 \times 10^6 \text{ m}^3$ to $2.4 \times 10^6 \text{ m}^3$ (about 8.3%), the average carbon sequestration will decrease from $4.8 \times 10^5 \text{ Mg year}^{-1}$ to $4.7 \times 10^5 \text{ Mg year}^{-1}$ (about 2.1%). However, if we consider higher levels of volume of ending inventory (again for the same level of total wood), there is a greater sensitivity in the supply of average carbon sequestered. A change of the volume of ending inventory from $2.50 \times 10^6 \text{ m}^3$ to $2.55 \times 10^6 \text{ m}^3$ (2%) is reflected in a decrease in average carbon sequestered from $4.6 \times 10^5 \text{ Mg year}^{-1}$ to $4.2 \times 10^5 \text{ Mg year}^{-1}$ (9.5%). As the volume of ending inventory is increased, the slope of the trade-off with average carbon sequestered becomes more negative and greater in absolute terms. Another relevant point on this trade-off is that as the total wood increases, the volume of ending inventory tends to decrease, and higher levels of total wood signify less trees and then lesser capacity to sequester carbon.

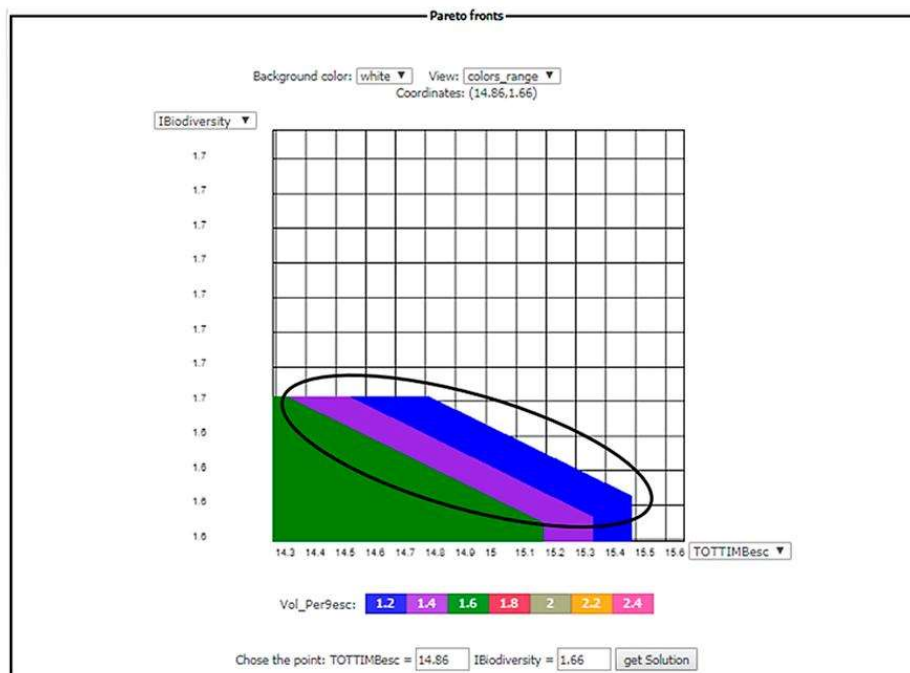


Figure 7. Interactive decision map showing the trade-off between three criteria: value of biodiversity indicator (ranges from 0 to 5 in its original scale; IBiodiversity) in the y -axis; total wood (10^6 m^3 ; TOTTIMBesc) in the x -axis, and volume of ending inventory—standing volume in last year of planning horizon (10^6 m^3 ; Vol_Per9esc) in the colored scale.

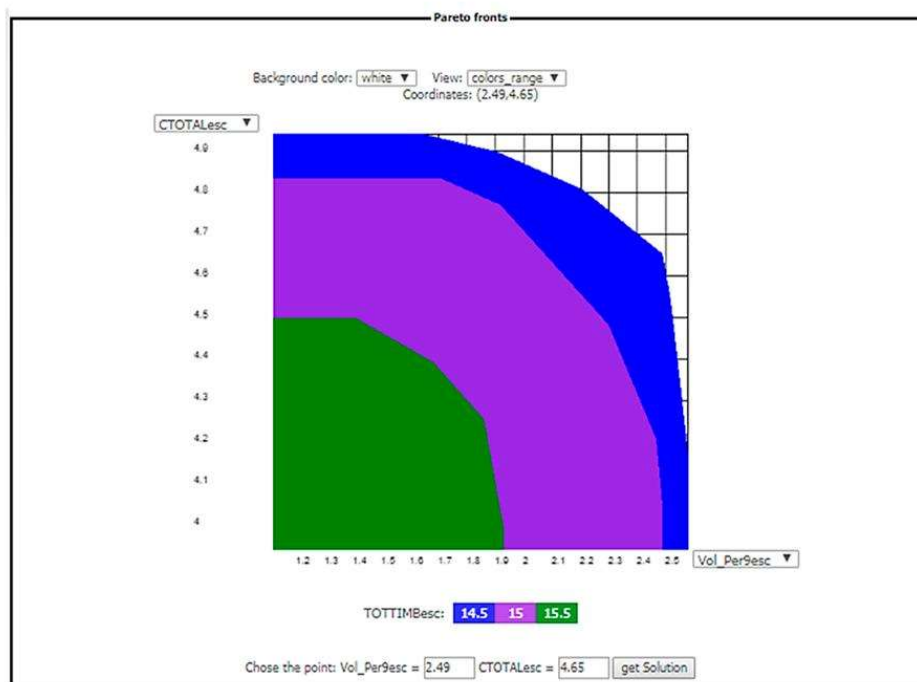


Figure 8. Interactive decision map showing the trade-off between three criteria: average carbon sequestration ($10^5 \text{ Mg year}^{-1}$; CTOTALesc) in the y-axis; volume of ending inventory—standing volume in last year of planning horizon (10^6 m^3 ; Vol_Per9esc) in the x-axis; and total wood (10^6 m^3 ; TOTTIMBesc) in the colored scale.

3.4. Stakeholder Feedback on Using the DSS

In this subsection, we analyze the survey responses from those stakeholders, forest managers, and other decision makers (a group of 18 people) who tested wSADfLOR. Results of the survey are presented in terms of ease of use (Figure 9) and utility (Figure 10). Considering all stakeholder responses (Figures 9 and 10), responses to all questions were predominantly neutral or positive. Another general observation is that stakeholder perceptions were consistently more positive with respect to utility (Figure 10) as opposed to ease of use (Figure 9).

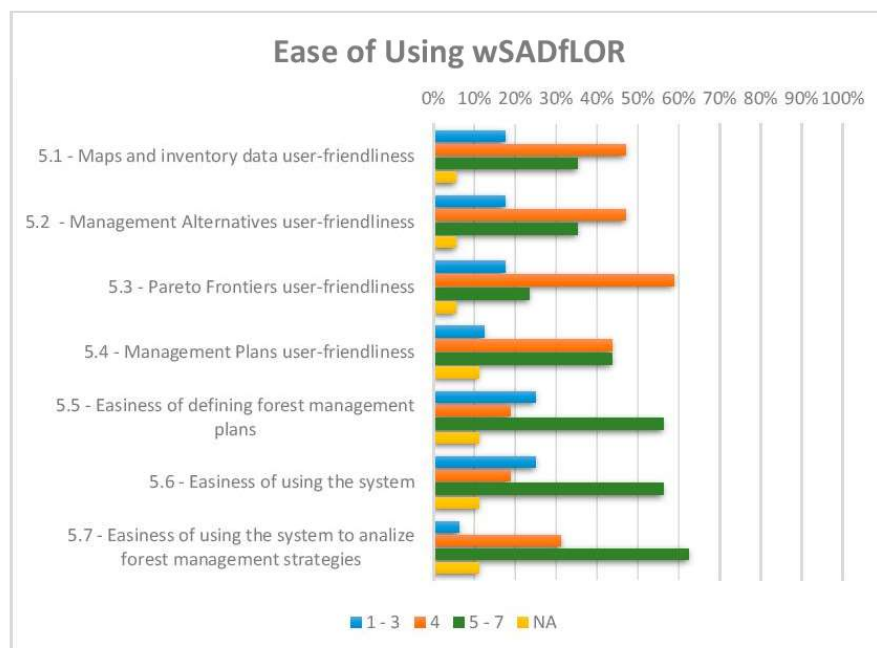


Figure 9. Questionnaire responses regarding the question on the easiness of use SADfLOR. Answers to each question were grouped into three categories: 1–3, 4, and 5–7, representing negative, neutral, and positive answers, respectively. NA represents not available (non-responses).

Looking in more detail at questions related to ease of use (Figure 9), stakeholders were generally neutral concerning user friendliness of interacting with maps and inventory data, design of management alternatives, and use of Pareto frontiers, but responses were generally positive concerning ease of use related to creation of management plans, overall use of the system, and analyzing management strategies. With respect to utility of the system, very strong positive responses were observed for usefulness of maps and inventory data, the process for generating management alternatives, management of a property, analyzing strategies, and efficiency in forest management. Stakeholders also demonstrated a very strong interest in continuing involvement in participation with wSADfLOR applications.

In order to further assess the functionality of wSADfLOR, the questionnaire included an open section so that stakeholders might provide suggestions for improving the system or for facilitating its use. Most respondents suggested the development of a user guide as well as of further training sessions. Some users were not familiar with Pareto frontiers, but after some training they could better

understand this decision tool, found it a very useful tool and manifested interest in working more with it. Moreover, some stakeholders acknowledged the usefulness of the system to support planning processes, while suggesting its expansion to include more models to address other forest species and other ecosystem services. The main questions posed by stakeholders during the workshop were more related to the interpretation of the optimization, decision, and analysis tools of the DSS. Some participants only required assistance with how to interpret the decision and analytic tools.

Finally, lack of stakeholder response was generally very low, the one exception being responses to Question 6.10, concerning the usefulness of wSADfLOR versus other DSS (Figure 10). In the latter case, six respondents had never used a DSS before, and so had no basis for answering the question.

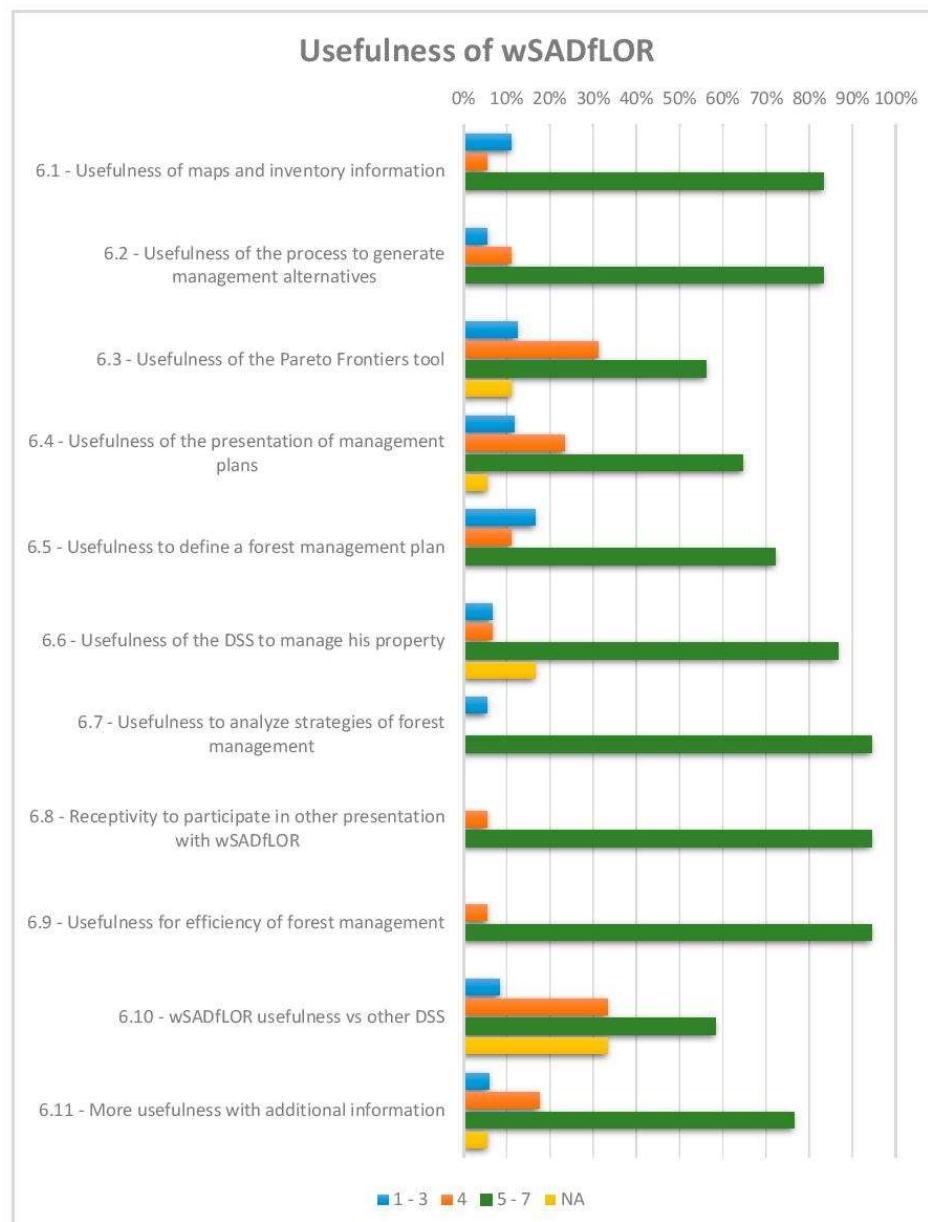


Figure 10. Questionnaire responses regarding the question on the usefulness of wSADfLOR. Answers to each question were grouped into three categories: 1–3, 4, and 5–7, representing negative, neutral, and positive answers, respectively. NA represents not available (non-responses).

4. Discussion

The wSADfLOR system was built to aid decision makers with preparing forest management plans. Landowners, governmental staff, forest managers, forest consultants and researchers can be potential users of this system as decision makers. The study area used in this work, ZIF_VS, is located in northwestern Portugal, covers 14,388 ha, and involves a very large number of owners. The decision makers have the challenging task of choosing between trade-offs of various forest ecosystem services and products that this study area can provide to them. The tools and methods of this study provide an example for developing similar forest management and decision strategies in other management areas that seek to promote the participation and collaboration of stakeholders (including landowners) in order to create a unique strategic and sustainable management plan that takes advantage of synergies of stakeholders' similar objectives. We found that the theoretical models and decision models can be put into practical use for aiding stakeholders in decision making tasks. Due to the spatial character of the forest management areas in Portugal in particular, the stakeholders must be alerted to the importance of collaboration. Although the geographically specific results of this study cannot be generalized, the analytical procedures can be easily replicated, and the methodology applied to other management areas.

The architecture of the system encompasses a nuclear module of information management by which the user can see, in a web GIS, all the management units which belong to the study area, and visualize information about each one, stored on the dynamic wGUI. The information management module provides all the needed data and information for the system, as well as interacts directly with the forest simulation module for the generation and manipulation of data to build the data matrix for forest management alternatives, which is then used to build the mathematical decision problem. Because the decision problem was built, the wGUIs on the forest planning methods module can help to choose among different decision maker's preferences for managing the study area. In the latter module, a Pareto frontier tool is available to show different configurations of trade-offs generated by the choices of the decision maker. The last module, the data analysis module, is useful for providing tabular, graphical, and GIS analysis of chosen amounts of forest ecosystem services and products according to the consensus solution.

In the past, decision support systems or tools similar to wSADfLOR were built and analyzed, namely a desktop version of a Pareto frontier approach [34] and a hybrid system to get consensus solutions when decision makers do not agree on a unique solution [47]. These authors emphasized the need for web-based systems. Finally, there are additional works which aim to study how to work with and analyze Pareto frontiers, and some of them were applied to a wide array of subjects in forest and natural resources management [28,35,36,44,48].

One of the advantages of the system presented here is that it is almost completely based on freeware, apart from the optimization software CPLEX, which is the only off-the-shelf commercial component of wSADfLOR, and Google Fusion maps. Running CPLEX potentially involves costs, but as wSADfLOR will be hosted on the servers at University of Lisbon, the users and researchers will not incur these costs. Currently, the individual responsible for the maintenance, upgrades, and wSADfLOR's software management is a researcher from our research team. Currently, wSADfLOR is available at <https://sadflor.isa.ulisboa.pt/ISA3/PHP/index.php>, and users only need authentication (username and password) provided by the wSADfLOR manager. We should note, however, that there is also a desktop version available for users who do not have internet access. The wSADfLOR is optimized for the Google Chrome browser, but we have done some experiments with IOS and Microsoft Edge, and the system seems to work well in these environments, but we want to guarantee and improve its responsiveness on other browsers, and make it available to a larger community of decision makers. The modular architecture of the system is very convenient for application to forest management and planning decision problems, and continues to undergo evolutionary development

at the Forest Research Centre of school of Agriculture due to the continuing need to address new forest ecosystem services and products. The Pareto frontier tool is evolving as a separate tool. There is an internal web-based version that only needs a formatted mathematical programming problem ready to be read with CPLEX or GLPK. Newer versions of this separate version of the Pareto frontier tool will be tested, and integrated in the wSADfLOR, if they prove to be useful advances. Apart from new functionalities or aesthetic improvements that can be considered in the Pareto frontier tool, its use in a server with more memory and processing resources could improve its performance with respect to generating the Edgeworth–Pareto hull and computing the solutions with CPLEX after a decision maker chooses the point on IDM. Moreover, although the Pareto frontiers included in this manuscript were developed by the authors as examples, and were not taken from stakeholder input, the Pareto frontier tool included in wSADfLOR provides a strategic forest management plan and policies to be followed by decision makers considering their own initial selection of concerns and objectives for managing the forest in the tradeoff analysis.

Another advantage of wSADfLOR concerns its potential to support participatory and collaborative forest management planning. In this context, the motivation is to produce systems or tools to facilitate the task of decision makers, and, at the same time, make transparent decisions with which the decision makers are comfortable ([15]). As the system encapsulates an a posteriori preference modeling approach ([28,29]), it does not require the elicitation of preferences by the stakeholders before they analyze the tradeoffs between ecosystem services. Borges et al. 2017 [29] highlighted the potential of this approach to support the negotiation of consensual solutions. Nevertheless, the use of the wSADfLOR tool does not explicitly support the collaboration of decision makers for building a consensus bundle of ecosystem services, but it can be used together with EMDS for that purpose as described in [47]. Most stakeholders who participated in the workshop considered wSADfLOR user-friendly and useful as seen from the analysis of questionnaires. Future research can continue to improve this system, following the suggestions of stakeholders, researchers, and other decision makers, with respect to new tools and functionalities, user-friendliness of the wGUI, system response time, visualization of the wGUI, and analysis of information.

5. Conclusions

wSADfLOR is a modular, web-based decision support system for forest management and planning. It includes modules dedicated to simulation, forest management and planning, decision making with a Pareto frontier tool, and a GUI for relevant data analysis. Looking to the future, and based on our experiences with stakeholder involvement discussed in this work, we see collaboration between the academic and the forest decision-making communities as key to the success of the continuing evolution of wSADfLOR.

The workshops with stakeholders promoted a constructive collaboration between researchers and stakeholders. Both groups learned more about the recent issues that landowners face in managing their properties, and the researchers may be able to suggest possible solutions, or alternatively identify new research needs related to the modeling and tools for helping decision makers better manage their properties as pieces of the greater forest mosaic.

Stakeholders play a critical part in the software development process, and with the experience of this workshop, we learned that they are open to express their opinions, and they like the idea that researchers are interested to collaborate with them in addressing their forest management issues. Our stakeholders demonstrated the desire to take part in more workshops like the one described in this paper, in which they can continue to learn and use these decision tools. Some of them revealed the importance of having more training support with the Pareto frontier tool. According to the insights learned from stakeholders, there is always room to improve the user-friendliness of the Pareto frontier tool and the way in which the system presents the results for management plans.

The use of wSADfLOR helps support collaborative planning in contexts characterized by multiple decision makers. Even if stakeholders are not able to select a single bundle of ecosystem services and to define a unique forest management plan, the tool helps narrow the range of choices and plans to be discussed. Other research demonstrated that it can easily be complemented with

EMDS DSSs (CDP and NetWeaver) for suggesting a unique bundle of ecosystem services as a solution for a forest management plan when multiple (groups of) decision makers do not agree on the composition of the bundle ([47]).

Future work with wSADFLOR looks to promote a more effective collaboration and negotiation among decision makers to select bundles of ecosystem services to input to an auctioning platform to attract voluntary payments for ecosystem services.

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ARTICLE 2: A web-based approach for visualizing interactive decision maps.

Article

A Web-Based Approach for Visualizing Interactive Decision Maps

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Abstract: This research expands the applicability of the Feasible Goals (FGoal) Pareto frontier multiple criteria method to display the Edgeworth–Pareto hull using interactive decision maps (IDMs). Emphasis is placed upon the development of a communication architecture to display the Pareto frontiers, which includes a client device, a web server, and a dedicated computation server implemented with sockets. A standalone application on the latter processes client-server requests and responses to display updated information on the client. Specifically, the dedicated computation server is responsible for calculating the information needed to generate the Edgeworth–Pareto hull. This is delivered to the web server to generate the IDM to be displayed on the client device. The key innovation of this work is a tool that is developed to aid decision-makers with a network-based computational architecture that includes a computational server constantly in communication with a web server for fast responses to client requests to represent IDMs. Results show that this innovation avoids time-consuming communication, and this approach to represent IDMs on the web facilitates collaboration among decision-makers because they can analyze several complex problems in different browser windows and decide which problem and solution better correspond to their aims.

Keywords: multicriteria decision analysis; Edgeworth–Pareto hull; Pareto frontier; web-based; decision tools; forest management



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1. Introduction

Considerable advances in the evolution of interactive decision maps (IDMs) have occurred—beginning at the end of the 20th Century and extending to the present time—due to improvements in the processing speed of personal computers and devices and, at same time, the increasing need to visualize tradeoffs on Pareto frontiers to aid decision-makers with multicriteria decision analysis [1]. Forest science, and environmental sciences more generally, are important contexts that can benefit from decision-making, using IDMs to support planning and multicriteria optimization, because decision-makers in natural resource management typically have to deal with multiple tradeoffs in their multicriteria optimization problems, including, for example, many possible combinations of ecosystem services and products. These tools target the increase in the efficiency and the effectiveness of forest management decision support system (DSS) tools and address the trends identified by Reynolds et al. [2] and Borges et al. [3]—namely, the need to consider multiple decision criteria and, at the same time, to be capable of responding to multiple stakeholders

with conflicting interests [4]. Currently, stakeholders tend to have a more active role in the participatory process. Therefore, contemporary DSS development tends to be linked to stakeholder involvement [5–9]. Web-based decision tools have been developed in order to help stakeholders and researchers in their decision tasks, making remote access to advanced decision methods and techniques possible [10]. The forestry literature reports several examples of DSSs to address multicriteria analysis and the management of ecosystem services [2,3,11–17]. Nevertheless, few are dedicated to the development and visualization of Pareto frontiers to support further collaborative management planning processes targeting the supply of several ecosystem services.

Some examples of multicriteria optimization problems involving tradeoff analysis include [18–20] and more recent studies carried out at the School of Agriculture (University of Lisbon) in collaboration with the University of Évora [7,8,21–23]. In the latter studies, the IDMs were either encapsulated in decision support systems as standalone packages or desktop application tools or used as application tools for building and showing Pareto frontiers on devices such as laptops and smart phones. Other web-based Pareto frontier decision tools related to forest and environmental sciences have been built, although using other methodologies, as in the work of Tóth et al. [4]: ECOSEL: an auction mechanism for forest ecosystem services.

All the web-based applications of IDMs mentioned above can be classified into two types of system architectures. On the one hand, there are systems that encapsulate a stand-alone tool developed in C++ in PHP code to communicate with the client computer, responding to its requests for calculations, to develop the visualization of Pareto frontiers for a client. On the other hand, there are systems in which a Java applet on the server computer performs all needed calculations and visualizations to be shown in the client by means of XHTML pages. Both types of applications are examples of web applications that implement remote rendering. Nevertheless, these systems are built on an architecture distributed over one or two machines. The main objective of this work is to show the possibility of communication between the client and PHP server to receive and respond to the requests of a client server. The PHP server is responsible for communicating with a dedicated computation server to generate the vertices and constraints of the Edgeworth–Pareto hull. This communication is performed using sockets [24] among the web server and computation server with a common free port and the computation server’s Internet Protocol (IP) address. After the Edgeworth–Pareto hull is built, the web-based graphical user interface (wgui) with IDMs is displayed on the client computer and updated according to the communications (sequences of requests and responses between the three computers). This is an innovation of the former architectures for building IDMs in forest management as it distributes calculations over three computers in the network, one of which is dedicated to generating the Edgeworth–Pareto hull.

The decision tool architecture of this research is thus motivated by the need to efficiently and effectively address collaborative management planning processes targeting the provision of several ecosystem services. By combining a client, a PHP server, and a computational server, it becomes very feasible to build IDM representations of problems with numerous constraints and decision variables for the client in close to real time. Moreover, it takes advantage of the network to perform the calculations and representation of IDMs instead of having an application running standalone on a personal computer. For collaborative decision-making in forest management, this architecture offers significant advantages to stakeholders as the tool is free and does not require the purchase of expensive hardware or software. The computation server is a particularly important element of the architecture because it enables solutions to very large IDM problems in close to real time in situations such as workshop settings.

This work aims to present: (a) an approach to develop web-based decision maps that allows decision-makers to develop their tradeoff analyses (how much they are able to sacrifice one objective to improve other objectives) more easily and promoting collaboration among decision-makers who have formulated their decision problem as a linear

programming problem; (b) a computational architecture capable of dealing with complex linear programs with a great number of decision variables and constraints by running the iterative algorithm for generating IDMs, displaying the Pareto frontiers and the solution chosen by decision-makers in a short period of time; (c) a flexible decision tool that can be used to analyze several concurrent problems at the same time in different Google Chrome (for which it is optimized) windows, providing the decision-makers with a good number of tools to make an informed decision concerning their main objectives.

The structure of this work encompasses: the Introduction that characterizes the state-of-the-art technology and provides the motivation for this research; the Materials and Methods, which include subsections to describe the optimization and visualization processes (Optimization and Visualization of Interactive Decision Maps) and to present implementations of these processes (Implementations); the Results section presents some outcomes of the use of the decision tool and includes a subsection with a forest management application; the Discussion section is dedicated to the discussion of our work; the Conclusion makes some final remarks about our decision tool.

2. Materials and Methods

2.1. Optimization and Visualization of Interactive Decision Maps

The methods of multicriteria linear programming can be classified according to the degree of decision-maker intervention [25–27]. According to these classifications, the multicriteria methods can be divided into three types: (i) the decision-maker chooses their preferences a priori; (ii) the decision-maker chooses their preferences in a previous dialogue phase and there is a sequence of computation phases and dialogue phases during the decision process in order to calculate new efficient solutions; (iii) the decision-maker takes their a posteriori decisions, before the set of proposed solutions is generated, from which the decision-maker will make their choice. The Pareto frontiers method shown in our IDMs falls into the third type.

To display the solution space for more than one criterion, a two- or three-dimensional graph needs to be used. The types of graph visualization include: (a) the representation of a set of efficient solutions in two or three dimensions as proposed by Tóth et al. [10]; (b) the representation of solutions for two to three criteria in a triangle as proposed by Climaco and Antunes [28]; (c) a Pareto frontier representation using IDMs, with the third criterion represented by colored sliders, each one with a different value associated to the third criterion. In the remainder of this paper, we focus on the representation of IDMs for a bicriterion Pareto frontier, which was first developed by Gass and Saaty [29] using standard parametric linear programming.

The representation using standard parametric linear programming is not an easy task if there are more than two criteria to be shown. Zeleny [30] and Steuer [27] demonstrate how linear multicriteria methods, based on the idea of Gass and Saaty [29], can be used to construct the list of all nondominated vertices. However, sometimes the vertices are not located regularly on the Pareto frontier, in which case they may fail to accurately represent the Pareto frontier. As a result, the nondominated faces are provided as well, and they are an analogue to the line segments for bicriterion Pareto frontiers. Although the access to all multidimensional information such as faces and vertices are relevant for representing the multidimensional convex hull, sometimes it is hard to formulate a decision from a very complex visualization. Then, decision maps are very useful in order to simplify the visualization and analyze such information, as we describe below.

For three criteria, we can efficiently construct a bicriteria tradeoff curve by fixing the third criterion within a range of values. However, for four or more criteria, and with hundreds or thousands of decision variables, it can take a lot of computational time to construct a decision map. Therefore, for the latter higher dimensional problems, some preprocessing work is needed to speed up the computations needed to generate the decision maps. A useful preprocessing algorithm developed by Lotov et al. [20] is based on

approximating the Edgeworth–Pareto hull (EPH) for all chosen criteria (see reference [20] for additional details).

The set X (feasible solutions set) is mathematically defined for the linear case by the following expression:

$$X = \{x \in \mathcal{R}^n : Hx \leq h\}$$

The EPH is the non-negative convex set in the space $\mathcal{R}^m$ ($m \geq 2$), delimited by the nondominated frontier, which is composed by the set of weakly nondominated criteria points and straight-line segments that connect these points. A point $z \in Z$ is considered a weakly nondominated point when there is not another feasible point which satisfies $z'_i \succ z_i$ ($i = 1, \dots, m$), $\forall z' \in Z \wedge z \neq z'$. We assumed the linearity of the system of inequalities due to the given matrix H and given vector h . Setting $f(x) = Fx$, where F is a given matrix, the EPH we want to find is [20]:

$$Z = \{z \in \mathcal{R}^m : z = Fx, Hx \leq h\}$$

Or alternatively,

$$Q^* = \{z \in \mathcal{R}^m : D^*z \leq d^*\}$$

where Q^* is the multidimensional set of feasible solutions on the decision space. The matrix D^* and the vector d^* need to be found. Given $x \in X$, all feasible values for decision variables, and $z \in Z$, all feasible values for the criteria, we can define the graph

$$Y^* = \{(x, z) \in \mathcal{R}^n \times \mathcal{R}^m : z \leq Fx, Hx \leq h\}$$

Thus, all we need is to construct the projection of Y^* onto $\mathcal{R}^m$, the set Z^* . This set can be found using convolution methods. The process is described in reference [20] (pp. 201–202). Figure 1a–e illustrates the process used for visualizing and generating Pareto frontiers with two or three criteria. The convex hull of the decision variables X (Figure 1a) was transformed into the criteria's convex hull Z (Figure 1b) by matrix F . Figure 1c shows in purple the set of nondominated solutions from set Z (supposing only one value for the third criterion, k), while Figure 1d extends this set to the axis and, finally, Figure 1e represents the frontiers for some values of the third criterion (k). In the case of four or five criteria, the graphical representation will be similar to (e), but with sliders on the bottom of the decision map for the user to choose the values to be fixed for the fourth and fifth criteria, and in this way change the representation of Pareto frontiers.

The optimization process in this decision tool lets the decision-maker interact with dynamic and web-based graphical decision interfaces (e.g., iterative decision maps). Based on the selected decision criteria, the decision-maker can analyze the results of the dynamic interactions that optimize his/her preferences. The concept of gamification [31] applies here to the conception and development of this decision tool, which focuses on graphical representation, dynamic interfaces, and real-time information.

The decision-maker can maximize or minimize criteria to be considered together in the multicriteria mathematical programming problem. The interface for generating the convex hull encompasses the criteria to be optimized, the maximum and the minimum values to be shown in the Pareto frontiers (or more correctly, Edgeworth–Pareto hull) and, finally, for generating the Edgeworth–Pareto hull set (an iterative process that is graphically represented). In the interface of the EPH, the decision-maker can visualize and interact with the graphical representation of tradeoff frontiers for the chosen set of concurrent criteria and choose the point on the frontier that satisfies his/her objectives.

To draw the EPH, the values of two criteria are considered, while the values for all other criteria are fixed. An algorithm, based on the Gift-Wrapping Algorithm for building Convex hulls [32], was implemented in PHP to sort the two-dimensional vertices of each slice of the EPH in the criteria space.

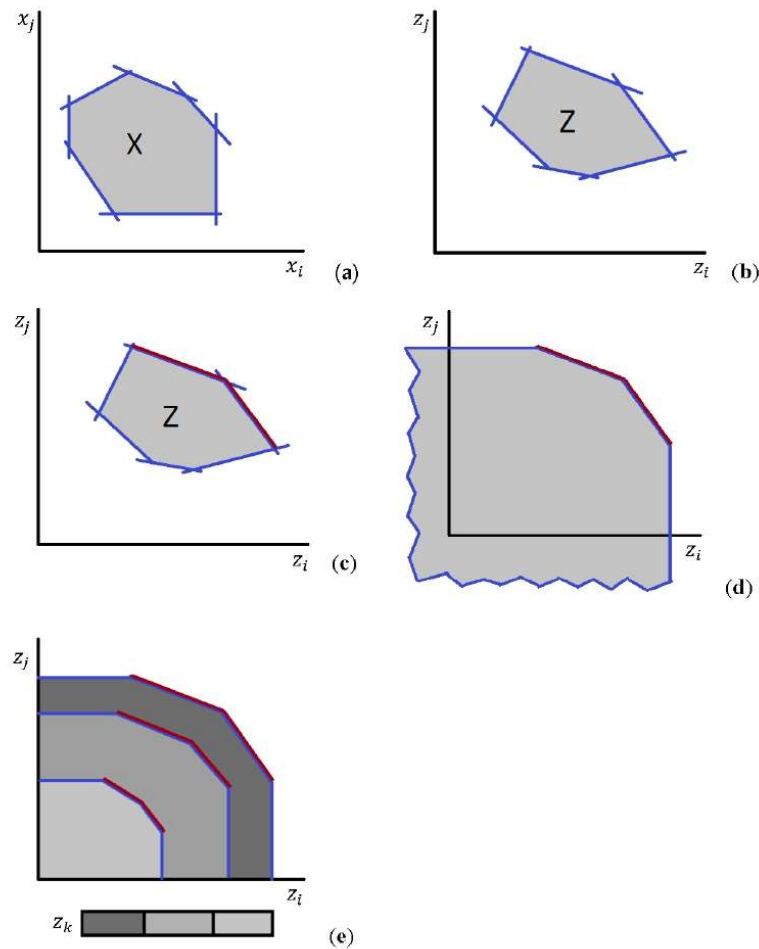


Figure 1. Generation of Pareto frontiers from the Pareto hull. (a) Initial convex hull of feasible solutions (x_i, x_j) . (b) Edgeworth–Pareto hull in the criteria decision space (z_i, z_j) . (c) Set of efficient solutions in the criteria decision space (z_i, z_j) . (d) Extension to the Pareto frontier for the efficient solutions set considering two criteria (z_i, z_j) in order to simplify the representation. (e) Pareto frontiers representation considering three criteria (z_i, z_j, z_k) .

Although the process of acquiring a solution based on the graphical representation of the EPH is conceptually quite simple, the computational process is complex. The decision-maker identifies a feasible goal directly on the IDM, first selecting a point on the map that maximizes his/her preferences. Before choosing that point, all criteria except two are fixed. The two criteria $(\hat{u}, \hat{v})$ are fixed when they click on the map and the goal vector $\hat{z} = (\hat{u}, \hat{v}, \hat{w})$ is identified ($\hat{w}$ is the vector of other criteria that the user can change by moving the sliders among the minimum and maximum values). The multicriteria optimization of the point chosen by the decision-maker is obtained as the solution of the following problem, where X is the set of feasible solutions of the original problem, the goal $\hat{z}$ is the reference point ([33]), ε_i represents small positive numbers, and m is the number of criteria

considered. So, without loss of generality, we can define this problem as the following optimization problem:

$$\text{minimize} \left\{ \max_{i=1, \dots, m} (\hat{z}_i - z_i) + \sum_{i=1}^m \varepsilon_i (\hat{z}_i - z_i) \right\} \text{subject to : } z = f(x), x \in X$$

The expression $\sum_{i=1}^m \varepsilon_i (\hat{z}_i - z_i)$ is important in this case to avoid weakly nondominated solutions [34]. The results (e.g., a strategic plan for forest management purposes) are shown in a CPLEX XML format or simply in a CSV flat file representing all basic variables of the last optimization interaction.

The next section describes which tools and computational architectures were developed in chronological order to program and display the IDMs with Pareto frontiers in the client.

2.2. Implementations

2.2.1. Standalone Implementation

Currently, most web browsers do not allow Java applets, and, for large linear programming problems (e.g., >1 GB of information), it is not computationally practical to run the problems in real time in any case. Instead, the standalone application Feasible Goals (FGoal) [21] can be run ahead of time to save the set of Pareto frontiers that have been optimized for a problem in order to be available when needed for decision-makers, stakeholders or other users. This standalone application, which evolved over the last few decades of the 20th century, has already proven very useful when there is limited access to the internet, or the optimization problem requires dealing with big linear programming files. The standalone application, in which users can develop and explore Pareto frontiers tradeoffs in real time or run and save a set of solutions ahead of time, to be shown later to decision-makers, has proven very useful for assisting with analysis and negotiation before decision-makers arrive at a consensus about which final solution will be chosen.

2.2.2. Java Applets Implementation

The first web-based implementation of Pareto frontiers was based on a client-server structure (Figure 2). The IDM technique separates the phase of approximation of the EPH from the phase of visualization. Thus, the server is used to approximate the EPH, and the Java applet is responsible for visualization of the Pareto frontiers. The server software was usually coded in C++ and Java, while Pareto frontiers were shown on client devices using XHTML and the Java Applet.

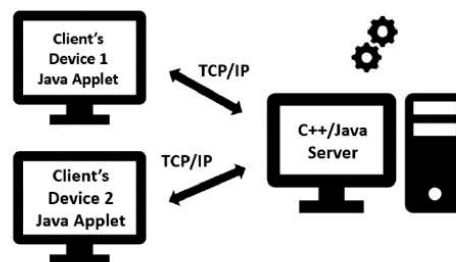


Figure 2. Communication client-server based on a Java Applet to show Pareto frontiers.

2.2.3. PHP Implementation

In this application, all the computational work required to generate all the vertices and constraints defining the EPH in each request from the client's device is performed by the computational server with algorithms written in C++. Subsequently, the EPH is built

using the PHP programming language (PHP version 5 and JavaScript version ECMAScript 2015) in the PHP server, and the results are finally displayed on the client side (Figure 3).

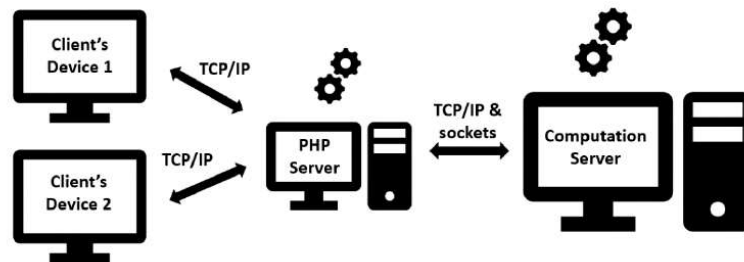


Figure 3. Communication between client's device, PHP server and computation server.

In this configuration (Figure 3), communication uses the Transmission Control Protocol (TCP), and only needs an internet protocol (IP) address and a port to make communication possible between the server and client. We defined a free port to communicate data between the two servers and a source address to permit the correct communication. In our case, the source address is our server PHP IP. Based on this source address, the socket is used to send and receive data from the computation server to generate the vertices and constraints of a mathematical programming problem, generating the EPH. This schema of communication is definitely convenient to acquire solutions and improve decision-making, because mathematical programming problems supporting forest management and planning typically need to be analyzed in real time by decision-makers.

The computational flow supported by our architecture (Figure 3) is best explained with a unified modeling language (UML) flowchart (Figure 4). The user starts the decision tool by entering, in the site, information in Google Chrome. The user uploads their formatted linear programming problem (problem.lp) that can be read with CPLEX, and which includes a table at the end of the flat file for identifying the criteria that will be used in the decision problem (initial wgui in PHP). The users choose the criteria to maximize or minimize the decision problem. They can impose some constraints for the minimum or maximum value for each criterion. After that, they submit the information provided and this starts the iterative process for generating the EPH. The algorithms used to generate the hull are described in Lotov et al. [20]. The convergence process stops when the discrepancy is less than 0.1 or the number of vertices in the hull is 64. This process runs in the computational server, which is communicating with the PHP server. A wgui was developed for the PHP server with the PHP and JavaScript languages, and with the available criteria and a progress bar to show the convergence. The PHP server reads the information provided by the computational server (vertices and constraints), sorts the vertices according to a Gift-Wrapping Algorithm [32], and makes all the calculations and configurations in order to show the IDMs in the client. When any changes in choices are made on the client side, the client communicates with the PHP server, the PHP server recreates the IDM and displays it on the client again (the Pareto hull is already generated). The wgui was developed with PHP and JavaScript. Finally, the users (on the client) choose one point in the IDM, and the optimization algorithm developed with PHP and CPLEX projects the solution to the closest point on the closest Pareto frontier using a Chebyshev distance. This is the final solution that can be stored in a CPLEX XML file or in a CSV file.

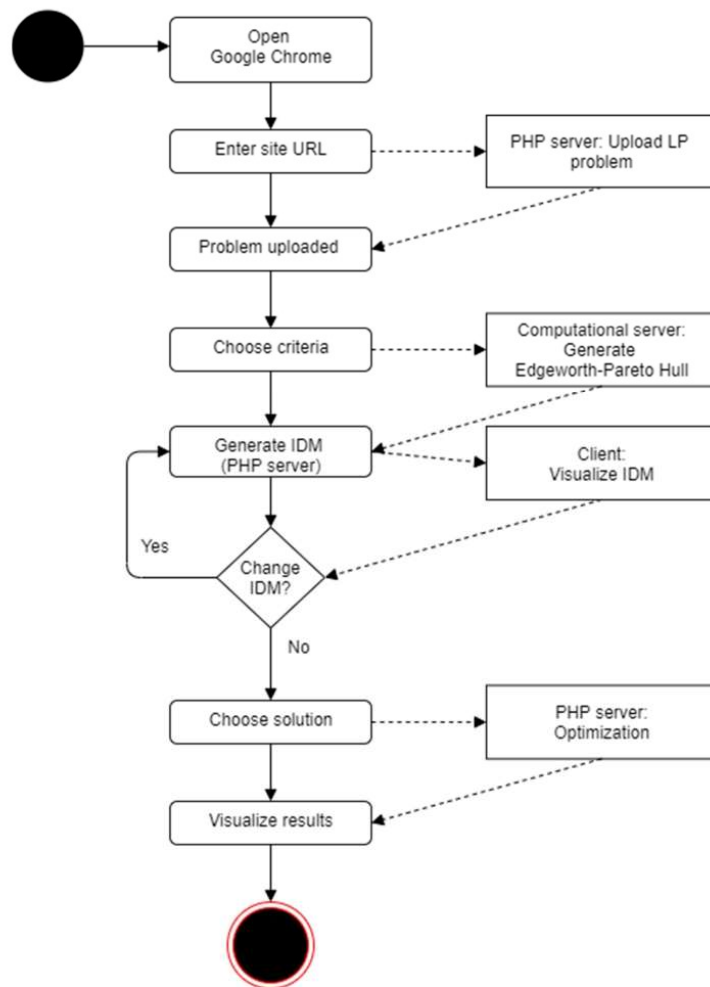


Figure 4. Decision tool's flowchart.

3. Results

In order to demonstrate our decision tool, we present an environmental decision problem that builds from the description by Lotov et al. (reference [20], pp. 32–34). It involves a region with a lake and a river that is used for intensive agricultural production. The water resources are used for irrigation and managers are concerned with the environmental impacts of the application of chemical fertilizers as well as with shortages of water in the lake. In our application, we considered the variables: *totcrop* (the sum of agriculture production in two zones of the region in percentage of the maximum), *leveldrp* (the level of the lake in percentage of the maximum), and *lakepol* (the additional water pollution in the lake in mg L^{-1}).

After uploading the *.lp file in the predefined format, we chose which criteria to maximize, minimize, or ignore for the construction of the EPH. Data were entered in the wgui (Figure 5) to run the iterative process to generate our Edgeworth–Pareto hull. In this example, we chose to maximize *totcrop*, and minimize *leveldrp* and *lakepol*. A constraint was introduced in the criterion *totcrop* ($\text{totcrop} \leq 80\%$), and all other criteria were uncon-

strained. The generation of the EPH ran in a few seconds, and its approximation was built with an associated error of 0.09649937 (discrepancy = 0.09649937 < 0.1; discrepancy reflects the error associated with the representation error of the real Pareto hull in the iterative process). The EPH is represented by 11 facets (polytope's features, line segments in 2D, triangles in 3D, etc.) and 15 tops (which are a generalization of slicing a reflexive polytope; a formal definition can be found in Bouchard and Skarke [35]). After the communication between the PHP server and the computation server, the EPH was defined and was ready to be represented in the IDMs as the known Pareto frontiers.

Cr	Name	Min	Max	Unit
Max	totcrop		80	
Min	leveldrp			
Min	lakepol			

Figure 5. Web graphical user interface (wgui) to choose the criteria to maximize or minimize, define any constraints on the criteria space (in this case $\text{totcrop} \leq 80\%$) and generate the Edgeworth–Pareto hull. This wgui shows the discrepancy between the convergence process and the real hull, the number of facets of the hull and the number of tops of the hull.

The result of our EPH computation has five colored slices and their Pareto frontiers (Figure 6). The five colors show the variation in the variable lakepol, with totcrop on the horizontal axis (limited by the constraint $\text{totcrop} \leq 80\%$), and leveldrp on the vertical axis. The configuration of the Pareto frontiers is easily changed by changing the criteria represented on the axes. The user can take a snapshot of the decision map (Figure 6), which is saved in a *.jpg file (hyperlink “Download as image”). After choosing a point on the IDM, the decision-maker can get the optimal solution according to his/her decision, as the corresponding point on the nearest Pareto frontier minimizing the Chebyshev distance (L_∞), similar to goal programming methodology. The optimization result was saved online either in a CSV file or in an XML file and represents a strategic management plan for forest management.

Figure 7 presents an alternative view of the IDM (in Figure 6), in which the polygon has only one slice (and one color), and instead of having the range of colors to represent the criterion lakepol, it has an additional slider to select values of lakepol. Thus, as in Figure 6, the configuration of the IDM changes when the selected value of the lakepol criterion changes. As we were maximizing the first criterion (totcrop) and minimizing the other two criteria (leveldrp, lakepol), if we increased the value of lakepol, the area of the polygon would increase.

Forest Management Application

In this section, we provide a small example of an application in forest management. The reader is referred to [36] for a detailed description of the case study area. The tool was used to support a collaborative planning process involving several stakeholders and targeting the provision of several ecosystem services over a 90-year planning horizon. Indeed, a version of this application of our decision tool is included in wSADfLOR [36]. Figure 8 shows the wgui used for the user to choose the criteria and additional constraints they want to include, for example, maximum and minimum limits for each criterion. Given that input, the EPH is generated. The criteria considered were: total wood volume harvested and thinned for all forest species considered (TOTTIMBesc, measured in 10^6 m^3); standing volume at the end of the planning horizon or volume of ending inventory (90 years), (Vol_Per9esc measured in 10^6 m^3); the average carbon sequestration during the planning horizon (CTOTALesc, measured in Mg year^{-1}); net present value (NPV, resulting from the

silvicultural operations and value of cut wood in the planning horizon, measured in 10^8 EUR). Definitions of discrepancy, facets, and tops are the same as in the previous example.

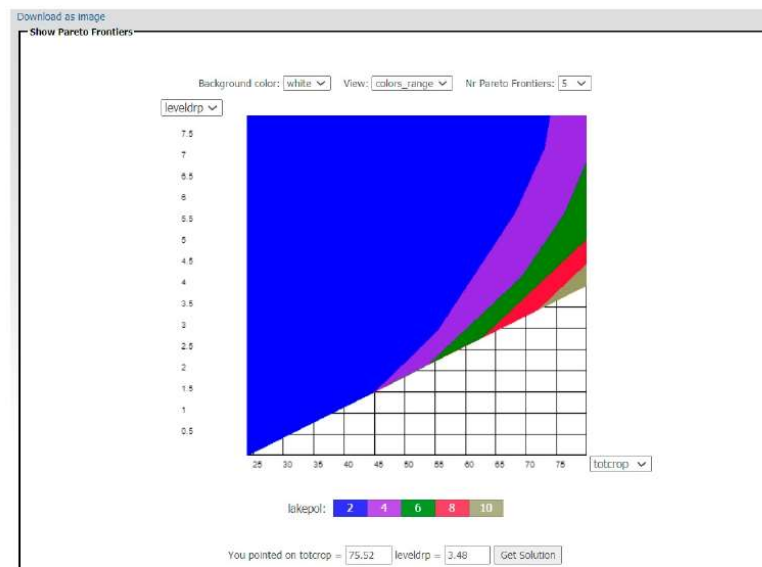


Figure 6. Representation of Pareto frontiers for the criteria totcrop (horizontal axis; in %), leveledrp (vertical axis; in %), and lakepol (represented by slices; in mg L^{-1}).

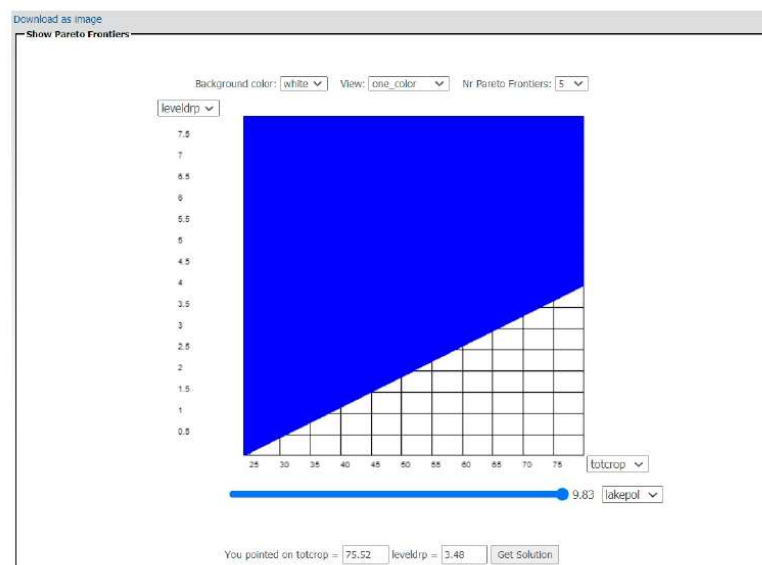


Figure 7. Representation of Pareto frontier with only one frontier (one color) with tradeoffs between totcrop (in %) and leveledrp (in mg L^{-1}) and the lakepol (in %) defined by the movement of the slider.

Generating Edgeworth-Pareto hull:...

100% completed!

Discrepancy = 0.0641343 | Facets = 41 | Tops = 15

Generate Criteria File

Cr	Name	Min	Max	Unit
Max	TOTIMBesc			(10 ⁶ _m3)
Max	Vol_Per9esc			(10 ⁶ _m3)
Max	CTOTALesc			(10 ⁵ _Mg_y)
Max	NPV			(10 ⁸ _eur)

Submit Data

Figure 8. Wgui for choosing the criteria to be used in the construction of the Pareto hull.

The IDM representation and the tradeoffs between the criteria are shown in Figure 9. They can be analyzed using the Pareto frontiers, one for each different value of colored scale (CTOTALesc), considering a given value of NPV = 0.64×10^8 EUR. In this example, if the user wants to analyze only a specific value of CTOTALesc, this is also an option as shown in Figure 10.

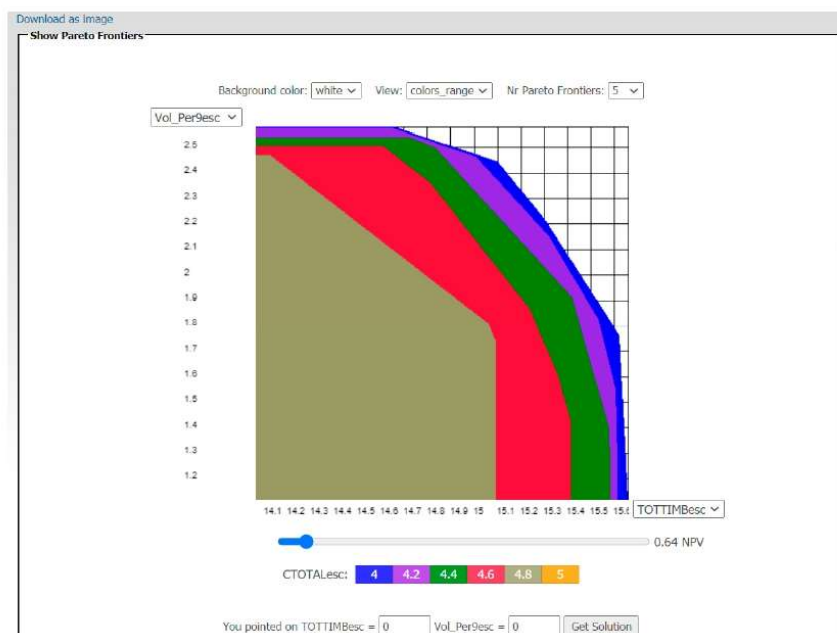


Figure 9. Interactive decision map showing the tradeoff between four criteria: volume of ending inventory (10^6 m^3 ; Vol_Per9esc) in the y-axis; total wood (10^6 m^3 ; TOTIMBesc) in the x-axis; the average carbon sequestered (Mg year^{-1} ; CTOTALesc) in the colored scale and the chosen level of net present value level (10^8 EUR ; NPV) in the slider ($0.64 \times 10^8 \text{ EUR}$).

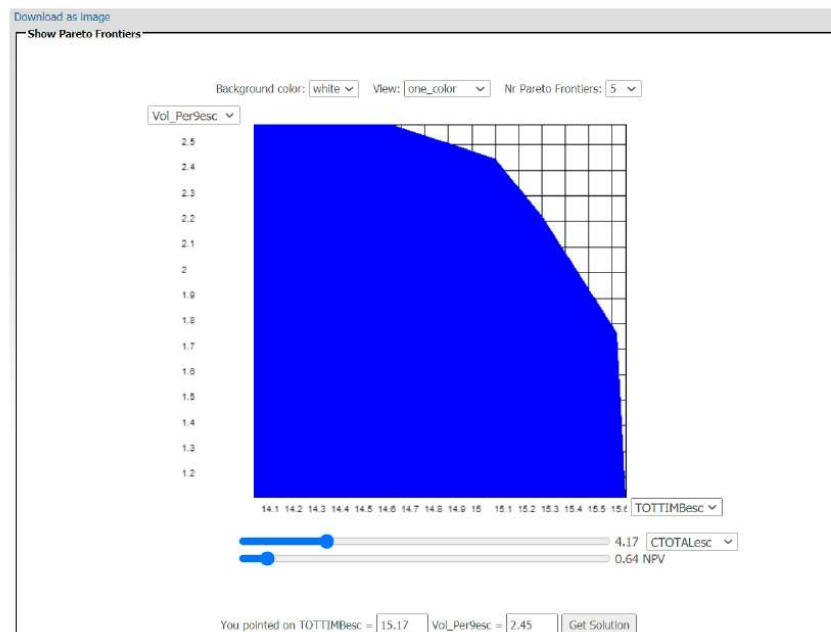


Figure 10. Interactive decision map showing the tradeoff between four criteria: volume of ending inventory (10^6 m^3 ; Vol_Per9esc) in the y -axis; total wood (10^6 m^3 ; TOTTIMBesc) in the x -axis; the chosen level of average carbon sequestered (Mg year^{-1} ; CTOTALesc) in the first slider ($4.17 \text{ Mg year}^{-1}$) and the chosen level of net present value level (10^8 EUR ; NPV) in the second slider ($0.64 \times 10^8 \text{ EUR}$).

4. Discussion

There are various ways to show tradeoffs in multicriteria decision analysis. Moreover, the visualization of IDMs may be supported by programming languages other than PHP with XHTML, (e.g., JavaScript or C++, R, Python) [4,28]. Some authors analyze the tradeoffs by using an explicit tri-dimensional visualization and can only infer the outline of Pareto frontiers as the tool only shows the vertices of the nondominated solutions [4]. Moreover, in order to analyze the tradeoffs among more than three criteria, we need to use another kind of representation for the nondominated solutions. The decision maps generated by the decision tool described in reference [28] are limited to a maximum of three criteria. The decision space is represented by a triangle and the tradeoff analysis was performed by analyzing the topologic relations among vertices and edges that belong to the solutions, which are represented by polygons inside the triangle. Our general computational methodology builds from earlier approaches [18–20] to increase the efficiency of the generation of IDMs. This web-based approach has a limitation of five criteria, while the standalone approach can deal with seven criteria, but it is easily extensible to deal with more than five criteria.

The development and visualization of the Edgeworth–Pareto hull is not a simple task. Reference [4] used a different method to visualize its points in a tridimensional space, whereas in the present work, as in previous works developed at the Forest Research Centre of the School of Agriculture in collaboration with University of Évora, we have used IDMs. Our representation of Pareto frontiers shows several two-dimensional frontiers, each one delimiting a space with a different color, representing different values of a third criterion for the values on the x - and y -axes of the first and second criteria. Responses to additional criteria can be represented by varying sliders at the bottom of the IDMs.

Currently, the decision tool presented in this study can handle variations in up to five criteria and is an interesting approach to visualize multiple color Pareto frontiers that makes it easier for decision-makers to select a point on the frontier. Further work on visualization and analysis with web-based IDMs is continuing to make the tool presented here more user friendly for decision-makers.

The current work demonstrates a new architecture for computing the Edgeworth–Pareto hull, based on sockets communication between the PHP server and the computation server (Figure 1). This architecture is very convenient, because, in this case, we have a powerful server dedicated to the computational effort of this task, thus making it possible to represent Pareto frontiers in a few seconds on the client device. Furthermore, the client can change the IDM built by the PHP server to be shown in the client device in a few seconds as well. Decision-makers, who want to make decisions and identify new feasible solutions in a short time, can benefit from this tool. Due to the fast processing time to display the IDMs, the decision-maker can run the tool in various tabs in the same Google Chrome session, and compare the different solutions and strategic plans resulting from these solutions. In terms of decision analysis, this is a positive point.

This web-based tool was built to run on the Google Chrome browser. Although we have partially tested it in Microsoft’s Edge and in Apple’s Safari with good performance results, it has not been fully tested, and some wguis may not respond as expected or may respond with some limitations. Thus, additional effort is needed to develop this tool, making it more responsive for other web browsers. A very similar tool has been integrated into the wSADfLOR forest and natural resources decision support system [36], and the latter has already been tested using an encapsulated standalone C++ package to generate the EPH. Akin to wSADfLOR, there are other works that have used encapsulated Pareto frontier tools as packages in C++ or Java, or Pareto frontiers developed with other architectures and methodologies, web-based or not. Other applications include those by references [4,7,8,21–23]. The present work is a result of experience gained in previous projects developed at the Forest Research Centre of School of Agriculture in collaboration with the Mathematics Department of the University of Evora, on developing and analyzing Pareto frontiers.

Our web-based decision tool is freeware and based on PHP web programming that continues to evolve with the evolution of web browsers, and the feedback of decision-makers and researchers. A very similar version, but without sockets, is already successfully implemented in wSADfLOR, but this current decision tool can easily be integrated into other decision support systems. Its architecture makes it easier to interact with IDMs from other places around the world with internet access. It has essentially been developed to serve the needs of analysis and planning for forest and natural resources management, but it can be useful in other fields as well. Reference [20] presents some examples of successful applications to environmental problems, real estate, and automobile businesses, but the method of building Pareto frontiers with the present architecture can easily be applied to any decision problem that can be formulated as a mathematical programming problem. It only needs a *.lp flat file, ready to be compiled by CPLEX or GLPK, and with the additional ScreenVariables block at the end of the file.

Finally, another important aspect to take into account is the user friendliness of the tool and helping decision-makers to be comfortable with their decisions. In these respects, decision-makers not only need good decisions, but transparent decisions [11]. This aspect of transparency in decision processes continues to drive the design of decision tools and decision support systems in business and science.

5. Conclusions

The architecture that we describe in this work makes it possible to deal with very high dimensional mathematical programming problems (e.g., numerous variables and constraints), because all computational effort needed for construction of the Edgeworth–Pareto hull is performed by a dedicated server. On one hand, this architecture supports

faster responses to the client, and consequently faster visualizations of the requests for changes by the client, with close-to-real-time responses. On the other hand, some problems were previously impossible to solve in reasonable times because of their complexity, but, with the proposed architecture, now the tradeoffs of Pareto frontiers can be shown and updated in almost real time even in the worst cases. This improved capacity enables a faster decision process and permits the use of the decision tool in any geographic location with internet access and at any time, with few or no limitations. The mathematical programming problem needs to conform to a predefined format in order to be well interpreted by the web Pareto frontier decision tool. This format is very similar to the traditional CPLEX or GLPK format, with a few more lines of code at the end of the file for the wgui to easily identify the criteria to be used in the optimization process.

Finally, while the decision support tool presented here represents a significant advance in evaluating tradeoffs on Pareto frontiers for high-dimensional decision problems posed by contemporary forest management, and the architecture described makes it quite feasible to handle such problems in real time in collaborative settings such as workshops, there are also additional opportunities to enhance the system with additional features to improve the quality and effectiveness of forest management decision-making, namely by extending it to address more than five criteria.

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CHAPTER IV

ARTICLE 3: Combining decision support approaches for optimizing the selection of bundles of ecosystem services

Article

Combining Decision Support Approaches for Optimizing the Selection of Bundles of Ecosystem Services

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Abstract: This study examines the potential of combining decision support approaches to identify optimal bundles of ecosystem services in a framework characterized by multiple decision-makers. A forested landscape, Zona de Intervenção Florestal of Paiva and Entre-Douro and Sousa (ZIF_VS) in Portugal, is used to test and demonstrate this potential. The landscape extends over 14,388 ha, representing 1976 stands. The property is fragmented into 376 holdings. The overall analysis was performed in three steps. First, we selected six alternative solutions (A to F) in a Pareto frontier generated by a multiple-criteria method within a web-based decision support system (SADfLOR) for subsequent analysis. Next, an aspatial strategic multicriteria decision analysis (MCDA) was performed with the Criterium DecisionPlus (CDP) component of the Ecosystem Management Decision Support (EMDS) system to assess the aggregate performance of solutions A to F for the entire forested landscape with respect to their utility for delivery of ecosystem services. For the CDP analysis, SADfLOR data inputs were grouped into two sets of primary criteria: Wood Harvested and Other Ecosystem Services. Finally, a spatial logic-based assessment of solutions A to F for individual stands of the study area was performed with the NetWeaver component of EMDS. The NetWeaver model was structurally and computationally equivalent to the CDP model, but the key NetWeaver metric is a measure of the strength of evidence that solutions for specific stands were optimal for the unit. We conclude with a discussion of how the combination of decision support approaches encapsulated in the two systems could be further automated in order to rank several efficient solutions in a Pareto frontier and generate a consensual solution.

Keywords: decision support; multicriteria decision analysis; multiple-criteria Pareto frontier methods; Criterium DecisionPlus; NetWeaver Developer; SADfLOR; Ecosystem Management Decision Support System

1. Introduction

Decision support systems (DSS) originated as important tools to aid decision-makers in business administration and industrial management in the 1960s [1]. DSS technologies were subsequently widely adopted in many other disciplinary areas, including natural resource management, in which DSS had become widespread by the mid-1980s [2]. Spatial DSS in particular began evolving in the late 1990s, coinciding with significant advances in geographic information systems (GIS) and computing

power in this timeframe [3]. The Ecosystem Management Decision Support (EMDS) system was one of the earliest examples of a spatial DSS for environmental analysis and planning [4,5], but the system has steadily evolved since that time, and remains in wide use up to the present [6]. The EMDS system is an application framework for constructing DSS for integrated, multiscale analysis and planning [7]. It supports landscape-level analyses through logic and decision engines integrated with the ArcGIS® geographic information system (GIS, ArcGIS 10.5, 2017, Environmental Systems Research Institute, Redlands, CA, USA), and the open source GIS systems QGIS, MapWindow, and DotSpatial.

The logic engine evaluates landscape data against a logic model designed in the NetWeaver Developer® system (NetWeaver2 Developer, 2017, Rules of Thumb, PA, USA) [8] to derive logic-based interpretations of complex ecosystem conditions, such as watershed conditions, wildfire potential, and landscape integrity. Logic modeling can be defined as a form of knowledge-based reasoning in which expert or tacit knowledge is used to construct a representation of how to think about and solve a problem [9]. In the EMDS context, in particular, logic is used to reason about the meaning of environmental states (e.g., given the data from the prescriptions on a management area, what can we infer about the score of each stand with respect to the criteria values for each nondominated solution?). EMDS decision models are built with Criterium DecisionPlus® (CDP, version 4.0, 2014, InfoHarvest, Seattle, WA, USA), which implements the Analytical Hierarchy Process (AHP; [10]), the Simple Multi-Attribute Rating Technique (SMART; [11]), or their combination. The AHP belongs to the general class of multicriteria decision models (MCDMs; [12]), while SMART derives from the closely related field of multiattribute utility theory (MAUT; [13]). Engines that implement Multi-Criteria Decision Methods (MCDM) solutions in particular have become increasingly common in contemporary DSS architectures for environmental decision support, beginning in about 1995, either as stand-alone MCDM solutions or as MCDM components of larger systems such as EMDS. In contrast, the use of engines that implement formal logic in environmental decision support is less common in contemporary systems. The latter have often been built by encapsulating growth and yield models and management planning methods rather than logic approaches [14]. However, logic processing has remained at the core of EMDS functionality since 1995 because of its capability to model the relatively large, complex, and often abstract problems associated with decision support for ecosystem management and adaptive management [6].

On the other hand, the web-based DSS SADfLOR builds from the experience of developing decision support systems to enhance forestry and natural resource management planning [15–17]. Its modular structure encompasses an information management module that encapsulates a web GIS and that is instrumental to organize administrative, geographic, and inventory forestry data. A simulation module projects the forest over time according to management options defined by stakeholders. It generates the management problem decision space. The latter is translated into a resource capability model by a matrix generator submodule. Decision-makers and stakeholders may input information that is translated into policy models (e.g., constraints on ecosystem services flows). An optimization module brings together the resource capability and the policy models. This module may be used to generate a solution to the management-planning problem by an a priori preference modeling multiple-criteria approach (e.g., goal programming). It may be used further to provide stakeholders and decision-makers with information about trade-offs between ecosystem services and trigger the application of an a posteriori preference modeling a multiple-criteria method (e.g., Pareto frontier). In this case, decision-makers can interact with the Pareto frontier submodule, analyze trade-offs, and select various nondominated solutions according to their preferences. In contexts characterized by multiple decision-makers, this submodule may be used to facilitate negotiation and consensus building (e.g., as seen in Reference [18]). Nevertheless, diverse and conflicting preferences and objectives suggest the potential of combining the multiple-criteria functionality of both the web-based SADfLOR and CDP and NetWeaver to further enhance the negotiation of solutions.

A multicriteria decision problem involves choosing one among various nondominated alternatives on how well those alternatives rate against a chosen set of structured criteria [19]. Thus, CDP and

NetWeaver as multicriteria DSS can be used to compare the performance of multiple alternative solutions following a predefined model with criteria values resulting from the optimization process of SADfLOR. Both knowledge-based DSS are useful to solve this problem. NetWeaver is based on fuzzy logic networks that are well suited as logic frameworks for integrating model results from various analytical systems, such as simulators, linear programs, Bayesian belief networks, and production-rule systems [20]. On the other hand, CDP provides extensive support for implementing this decision process, including setting priorities, explaining the derivation of conclusions, checking model robustness, and providing trade-off analyses. The criteria are weighted in terms of importance to the decision-maker and, in the end, after the evaluation by the model, the alternatives are ordered by their decision scores as a prioritized ranking of alternatives by preference [19].

In the present study, we describe the use of a combination of decision support approaches encapsulated in the EMDS and the web-based SADfLOR systems to recommend optimal selections of alternative management combinations in the study area. Firstly, we use a spatially explicit multiple-criteria method within SADfLOR to generate both the decision space and the criteria space of the management-planning problem. This decision approach presents ecosystem services trade-off information in the form of Pareto frontiers to support the negotiation of alternative bundles of ecosystem services. In the first aspatial phase of the analysis, we use the CDP component of EMDS to support further this negotiation by performing a multicriteria decision analysis (MCDA) that assesses the aggregate performance of selected points on the Pareto frontier for the study area as a whole. In the second spatial phase of the analysis, the NetWeaver component of EMDS is used to recommend selection of specific points on the Pareto frontier in specific landscape units of the study area. In the discussion, we conclude by considering the advantages and complexities of employing a hybrid DSS such as EMDS/SADfLOR to realize the potential of the combination of the decision approaches to support collaborative forest ecosystem management planning.

2. Materials and Methods

2.1. Study Area

For this study, we considered the Zonas de Intervenção Florestal (ZIF) Paiva and Entre-Douro e Sousa (ZIF_VS), located in northwestern Portugal (Figure 1). The maximum elevation reaches about 700 m, yearly average temperatures range between 10 °C and 15 °C, and the main soil types are anthrosols, leptosols, and regosols. It spans three counties (Castelo de Paiva, Penafiel, and Paredes), covering an area of about 14,388 ha, and it is classified into 1976 stands for forest management purposes. The area is dominated by pure eucalypt (*Eucalyptus globulus* Labill) stands and mixed stands of eucalypt and maritime pine (*Pinus pinaster* Ait.)—about 66% and 33% of the ZIF_VS area, respectively, and hardwoods (mainly chestnut in 1% of the case study area). Community (local parish) property accounts for 35% of the ZIF_VS area. Medium and large private properties (area greater than 5 ha) extend over 60% of the ZIF_VS area. The remaining 5% is owned by small or very small forest owners [19]. The stands are managed by each landowner with the support of the Local Forest Owners Association that is responsible for the development of the joint landscape-level management plan. The most important products are eucalypt pulpwood and maritime pine sawlogs, but the range of ecosystem services includes further hardwood (chestnut) sawlogs, carbon sequestration, and biodiversity. ZIF Paiva stands belong to 185 associated landowners, while ZIF_VS has 191 associated landowners. The web-based SADfLOR DSS has evolved with the involvement and participation of several stakeholders, ranging from the Instituto da Conservação da Natureza e das Florestas (ICNF), to the forest industry and nongovernmental organizations (e.g., forest owners associations) [15,21]. It was used to simulate all ZIF_VS stand-level prescriptions (59,133) over a 90-year planning horizon.

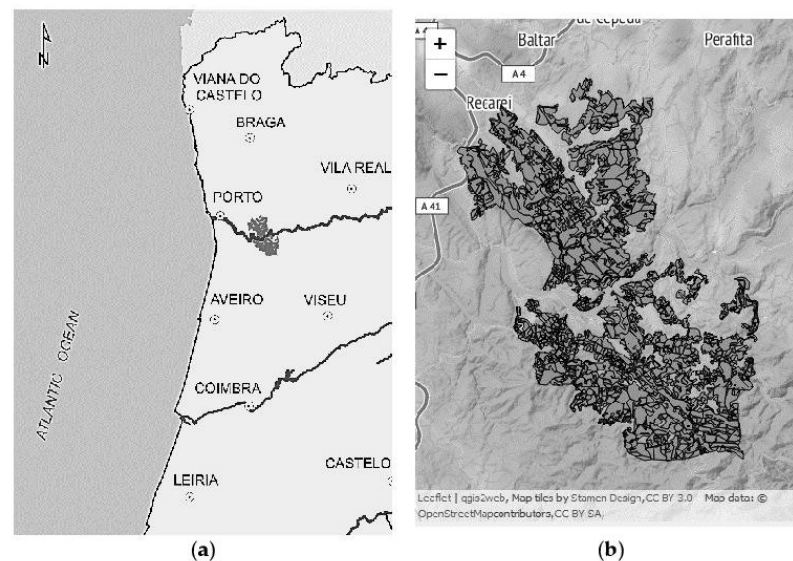


Figure 1. Zona de Intervenção Florestal (ZIF) Paiva and Entre-Douro e Sousa. (a) location of the study area in Portugal; (b) classification of the study area into stands.

2.2. Overview of Decision Tools and Analytical Steps

In this work, we focused on the integrated application of three decision support approaches encapsulated in two DSS. The decision support approaches were: a multiple-criteria Pareto frontier method available in the web-based SADfLOR DSS, an aspatial strategic MCDA method available in the Criterium DecisionPlus (CDP) component of the EMDS DSS, and a spatial logic-based approach available in the NetWeaver component of EMDS.

The web-based tool encapsulates a multicriteria mathematical programming model and displays the trade-offs between ecosystem services in the form of Pareto frontiers. This analysis supports the selection of packages of ecosystem services according to the preferences of decision-makers. For that purpose, the ecosystem services are classified by the tool into two sets of criteria. The first includes wood products (e.g., total wood), while the second includes nonwood products as well as nonmarket services (e.g., biodiversity). The interface of the web-based tool asks the decision maker whether the provision of each ecosystem service (criteria) is to be maximized or minimized. After the selection by decision-makers of the list of ecosystem services to maximize or minimize in the bundle, the tool launches the process for generating the Pareto frontiers (e.g., as in References [22,23]). This information provides a basis for the negotiation of the packages of ecosystem services to be supplied by the decision-makers [18]. These packages correspond to nondominated points in the Pareto frontier. After its selection, the web-based tool triggers the solution of the multicriteria mathematical programming problem associated to each point, i.e., it retrieves the management plan that may convey the corresponding package of services.

In this study, an aspatial strategic MCDA in CDP and a spatial logic-based approach in NetWeaver were both used to choose the best nondominated solution among a set of alternatives generated by the Pareto frontier tool in SADfLOR. CDP is an MCDA DSS that is useful for ranking alternatives based on how well each rates against a set of decision criteria [24]. CDP implements both the analytic hierarchy process (AHP; [10,25]) and SMART [11] techniques. We use the AHP method to derive weights on criteria and subcriteria by the pair-wise comparison technique, but we use SMART to score the performance of the attributes of alternatives. The combined use of AHP and SMART offers the

advantage of eliminating, or at least greatly reducing, the well-known problem of rank reversal of alternatives in the classic AHP approach, in which scores on attributes of alternatives are derived by pair-wise comparisons [24]. NetWeaver provides a logic-based framework that is useful to evaluate the conflicting alternative solutions chosen by different (groups of) decision-makers. It has two features with respect to the learning process: NetWeaver models provide detailed, permanent documentation about how we conceive that a system should be evaluated, and the modular architecture of logic models is well suited to the incremental, evolutionary adaptation of the models as knowledge changes [24]. The overall analysis was performed in three steps:

1. Generation of the criteria space and selection of six alternative points on the Pareto frontier for subsequent analysis.
2. Aspatial multiple-criteria decision analysis of the aggregate performance of points on the Pareto frontier for the entire study region.
3. Spatial logic-based assessment of points on the Pareto frontier for individual stands of the study area.

Details of these three analytical steps are presented in the next three subsections and a flow chart of this methodology is provided (Figure 2).

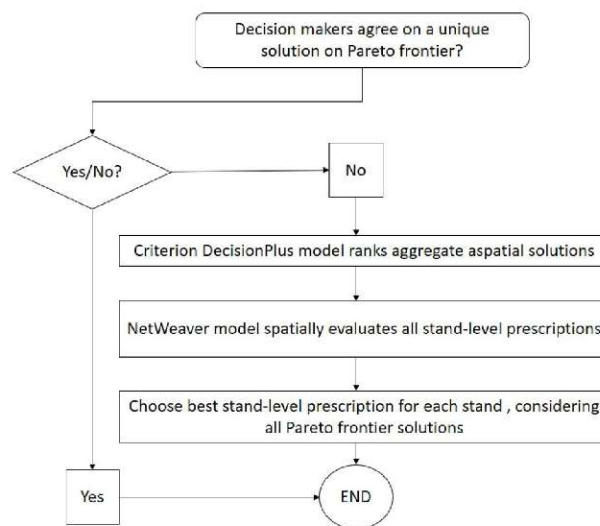


Figure 2. Decision support flowchart.

2.3. The Criteria Space and the Pareto Frontier

A multicriteria mathematical programming method within the web-based SADfLOR was used to define the forest management planning decision space. This was translated into the corresponding criteria space and Pareto frontiers by the interactive decision map technique. In this application, we emulated a negotiation process for the selection of six bundles of ecosystem services (six points in Pareto frontiers) for further analysis. The tool read this information and triggered the solution by the multicriteria mathematical programming method to find the corresponding six management plans.

2.4. Aspatial Multiple-Criteria Decision Analysis

A multiple-criteria decision analysis model within the CDP component of EMDS was used to compare the performance of multiple points on the Pareto frontier with respect to criteria and weights

determined by a decision-maker or group of decision-makers. In this aspatial model, we considered the same criteria used in the first analytical step, but with solution variables aggregated into two primary sets of criteria: Wood Harvested and Other Ecosystem Services. In practice, the criteria weights will vary individually by decision-maker or by consensus in the case of a group. However, for purposes of demonstration in this study, we assumed a consensus across all decision-makers, in which the primary criteria are equally weighted. The key analysis metric for CDP is a measure of utility that expresses the preference among Pareto points, given the weight assigned to the primary criteria in the CDP model. Note that this is a classical strategic MCDA analysis in which the alternatives are the aggregate results summarized by alternative solution points on the Pareto frontier.

2.5. Spatial Logic-Based Assessment of Points on the Pareto Frontier for Individual Stands

In the final step of the analysis, we used the weights developed in the second analytical step in a logic model that was executed by the NetWeaver component of EMDS to assess performance of the delivery of ecosystem services at the scale of individual stands. Each of the six nondominated points from the Pareto solution was associated with a map that was evaluated in EMDS, because the input data vary with the Pareto point selected. The NetWeaver model is structurally and computationally equivalent to the CDP model, but the key NetWeaver metric is a measure of strength of evidence. In this application, the topmost logic topic in the model was evaluating evidence that a particular Pareto solution delivers ecosystem services in a stand. One map of NetWeaver outcomes was generated in EMDS for each Pareto point. Maps are symbolized in terms of degree of evidence that the solution delivers ecosystem services. This analysis disaggregated the strategic MCDA analysis to individual stands.

The data inputs to NetWeaver included the ecosystem services target values in the six bundles selected by stakeholders and the corresponding management plans (e.g., one prescription per stand). Each data input to NetWeaver was evaluated by a fuzzy membership function that returned the strength of evidence that the observed stand-level value contributed to delivery of ecosystem services. Fuzzy membership functions in NetWeaver were scaled to the interval $[-1, 1]$, in which -1 indicates no evidence, and 1 indicates full evidence. For each data input, the function was normalized to the observed data by setting the X-value corresponding to an evidence value of -1 as the minimum of the data distribution, considering the data range in the variable across all six Pareto solutions and all land stands. In general, data values were significantly right-skewed, so the X-value corresponding to an evidence value of 1 was set to the 90th percentile of the distribution for each input in order to provide a more useful distribution of outcomes on each input variable.

3. Results

3.1. The Criteria Space and the Pareto Frontier

The participation of various forest actors in forest decisions is increasingly relevant to strategic forest management and planning. Decision-makers interact with the Pareto frontier tool and can get several nondominated solutions according to their preferences and compare them to different levels of ecosystem services achieved, taking into account the trade-offs between them. When we have various (groups of) decision-makers, it may well happen that, even after the display of production possibility frontiers and trade-off information, no consensual solution is arrived at. In this case, there will be no single point on the Pareto frontier for the management area that provides a solution simultaneously optimal for the differing preferences of the decision-makers. In this research, we assumed that this was indeed the case and we emulated the selection of six solutions corresponding to preferences of six groups of decision-makers (Figure 3). The solutions corresponding to the six points in the Pareto frontier (Table 1) resulted from the maximization of the five criteria: Total Wood (harvested volume and thinned volume), Volume of Ending Inventory, Average Carbon Sequestration (the aboveground carbon pool: stem, leaves, branches, and bark), Net Present Value, and Biodiversity Indicator (IBiodiversity).

In this research, the value of IBiodiversity is a function of the stand age and composition and ranges from 1 to 5.

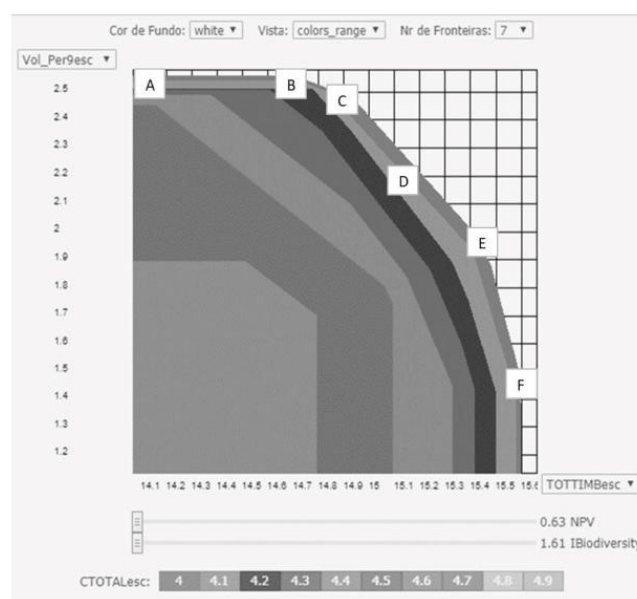


Figure 3. Trade-offs between three criteria. In the x-axis TOTTIMBesm Total Wood (10^6 m^3). In the y-axis, Vol_Per9esc, Volume of Ending Inventory (10^6 m^3). Each of the seven decision maps corresponds to a level of COTALesc, Carbon Sequestration ($10^5 \text{ Mg year}^{-1}$). The other criteria, Net Present Value (10^8 € ; NPV; on the first slider) and Biodiversity Indicator ([0, 5] (IBiodiversity; on the second slider) have been fixed at 0.63 and 1.61, respectively. Solutions A–F correspond to six alternative sets of criteria values.

Table 1. Selected results for ecosystem services for the planning horizon of 90 years ^a for the Zonas de Intervenção Florestal Paiva and Entre-Douro e Sousa (ZIF_VS).

Ecosystem Service	Unit	Point A	Point B	Point C	Point D	Point E	Point F	Final Solution
Total Wood	10^6 m^3	14.4517	14.7226	14.9184	15.2008	15.4526	15.5948	14.4762
Maritime Pine Wood	10^5 m^3	4.3913	4.4587	5.0933	5.3523	4.8534	5.4398	3.3605
Eucalypt Wood	10^6 m^3	13.4644	13.7243	13.8566	14.1096	14.3054	14.4226	13.6267
Chestnut Wood	10^6 m^3	0.1604	0.1601	0.1418	0.1418	0.2468	0.1862	0.1560
Volume of Ending Inventory	10^6 m^3	2.5659	2.5626	2.4784	2.1508	1.9126	1.4348	2.5350
Average Carbon Sequestration	$10^5 \text{ Mg year}^{-1}$	4.4148	4.4115	4.4073	4.4197	4.3615	4.3637	4.5049
Net Present Value	10^8 €	0.6575	0.6542	0.65	0.6624	0.6465	0.6596	0.6490
Value of Biodiversity Indicator	[0, 5]	1.657	1.6556	1.6465	1.6468	1.6425	1.6446	1.6682

^a The positions of the solution points, A to F, are shown in Figure 1.

There are interesting trade-offs and findings (Table 1). This set of solutions was chosen for representing different possible choices of decision-makers, with some variations of the values for each criterion in the decision map. The growth of Total Wood from point A to point F is mainly explained by the increase in values of Eucalypt Wood. On the other hand, it seems that, as Maritime Pine Wood is decreasing, Chestnut Wood is increasing, and vice-versa. In fact, there is another trade-off between these ecosystem services due to the possibility of conversion of Maritime Pine stands into Chestnut stands in the first three periods of planning horizon. Although the Net Present Value (NPV) was

included as a criterion to be optimized, it does not vary much in the selected solutions, and it does not seem to have a strong trade-off with the remaining data inputs.

The values of IBiodiversity are relatively low. However, the main species in this case study is *Eucalyptus globulus*, and this is the species among all considered species with the lowest values of biodiversity, so the values for average IBiodiversity are consistent with this observation. Generally, we can see that the Average Carbon Sequestration reaches higher levels when we have lower values of Total Wood, which makes sense given the nature of this data input. Another relevant point is the fact that the NPV tends to have higher values when the levels of Total Wood are higher. In fact, one of the most important effects for the NPV is due to the profit of harvested volume or thinned volume that is sold, in this case, as standing wood.

3.2. Aspatial Multiple-Criteria Decision Analysis of the Pareto Frontier

The aspatial MCDA model designed in CDP considers the ecosystem services from the six nondominated solutions (Table 1) as attributes, which are aggregated into two groups of decision criteria: Wood Harvested and Other Ecosystem Services (Figure 4). Total Wood is not included in the MCDA model because it is a linear combination of the values of the three species, and NPV is not included as it reflects wood sales and it is very correlated with wood harvested criteria (Table 1). The six nondominated solutions (A–F) represent the model alternatives, whose attribute values have been aggregated over land stands in the study area. The overall goal of this model is to identify the solution that provides the best combination of ecosystem services. Weights on the two criteria and weights for the contributions of attributes under each criterion were treated as equal strictly for demonstration purposes. Considering the large number of landowners who might represent at least several distinct stakeholder groups, use of equal weighting can be thought of as a default specification for a potentially diverse set of owner perspectives. In this context, the model ranked first solution D (0.586) (Figure 4), partly as a consequence of its higher contribution to the average carbon stock.

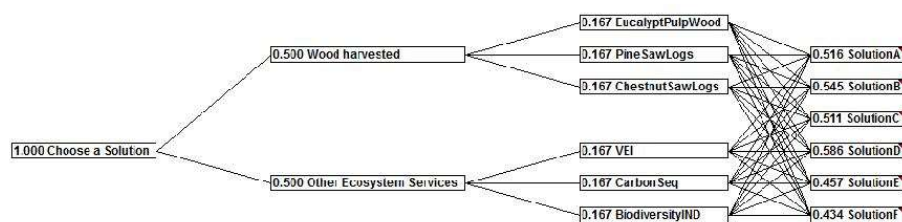


Figure 4. The Criterium DecisionPlus (CDP) model to choose the best nondominated point from the Pareto frontier.

The analysis of model sensitivity in CDP demonstrated that the resulting model was somewhat sensitive with respect to identifying solution D as the top-rated alternative, given that the most sensitive criterion/attribute combination had a critical crossover value of 6.4%. In other words, the absolute value of the weight on the most sensitive combination would have to increase by only 6.4% before solution B would outrank solution D. The convention, recommended by References [10,25] is that the most sensitive combination in the sensitivity analysis should have a crossover value of at least $\pm 10\%$ to robustly conclude that the top-ranked alternative is indeed the best. Considering the contributions of the primary criteria to the overall decision score, it can be seen that solutions A to D are more or less comparable in terms of the overall decision score for each alternative, but there are significant differences among these four alternatives in terms of their contributions to other ecosystem services, and solutions A to D clearly perform better than either solution E or F with respect to other ecosystem services (Figure 5).

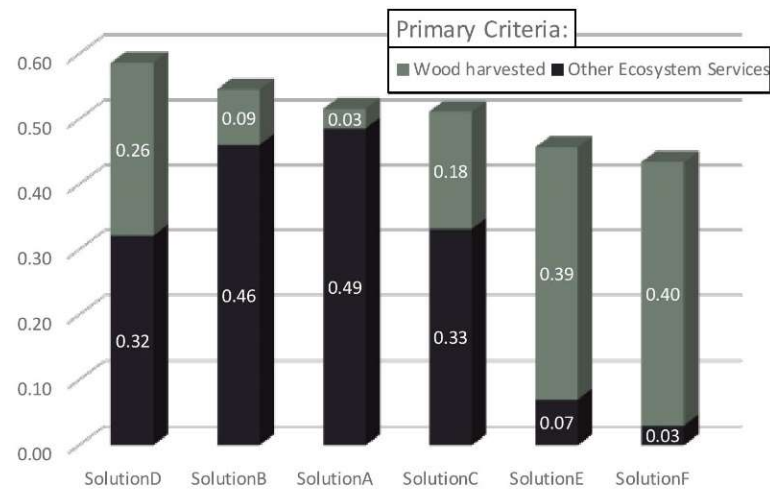


Figure 5. Contributions of primary decision criteria (Figure 4) to the overall CDP utility score for the six solutions (A to F) from the Pareto frontier analysis (Figure 3).

3.3. Spatial Analysis of Pareto Points for Individual Stands

Results from the previous section showed that solution D performed best with respect to delivery of ecosystem services when we consider the aggregate performance of each solution for the entire study area over the 90-year planning horizon. In the spatial phase of the analysis, we next look at how the six nondominated solutions performed at the scale of individual stands. For the spatial analysis, we used a NetWeaver model (Figure 6), executed in EMDS, that was structurally and computationally equivalent to the aspatial CDP model (Figure 4) to evaluate performance for each stand (Figure 7).

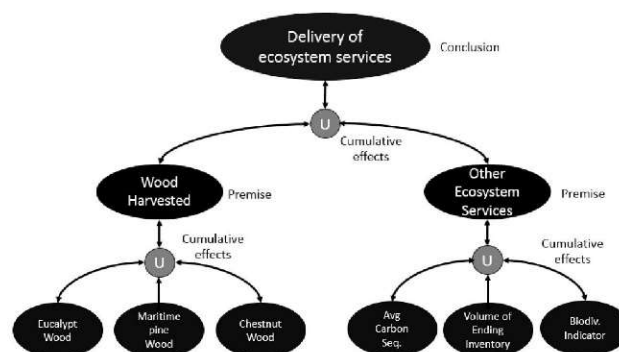


Figure 6. NetWeaver model to assess delivery of ecosystem services for individual stands. Data inputs at the stand level vary by Pareto solution (A–F), so this model is evaluated in EMDS with a separate assessment for each Pareto solution (Figure 7). Each oval represents a logic topic. Gray topics shown at the bottom of the diagram are elementary topics that evaluate data inputs with fuzzy membership functions.

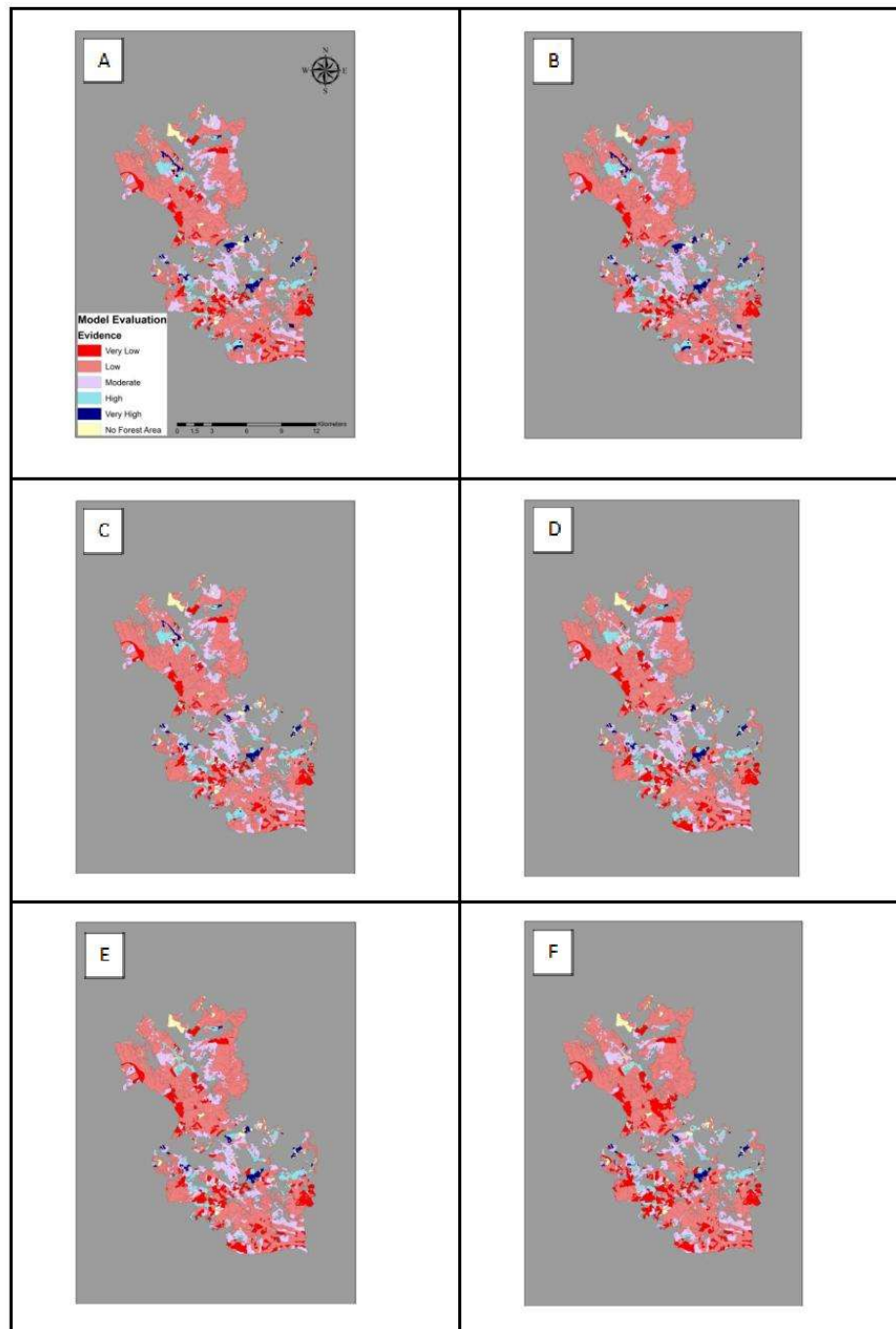


Figure 7. Evaluation of individual stands for solutions A to F from the Pareto frontier (Figure 3) with the values of variables per ha using the same NetWeaver model used for evaluating the best point (Figure 6). The percentile 90 was used as the maximum.

Due to the combination of the map scale and the five-class map symbology (Figure 7; $[-1;-0.6]$, very low; $[-0.6;-0.2]$, low; $[-0.2;0.2]$ moderate; $[0.2;0.6]$ high; $[0.6;1]$ very high), the performance of the six solutions appears very similar, although a close examination of outcomes reveals small differences in the optimal solution choice for individual stands (see the set of map enlargements in the Figure 7). To better discriminate among the performance of solutions at the scale of stands, scores for all solutions were compiled into a single map layer and stands were coded according to the best solution (Figure 8). Pareto solutions D (1229 polygons) and B (623 polygons) clearly dominate the map (Figure 8), with a few scattered occurrences of solution A (64 polygons), F (16 polygons), C (3 polygons), and E (2 polygons). The corresponding solution in the criteria space is characterized by the highest values of average carbon stock and biodiversity and the lowest net present value (Table 1).

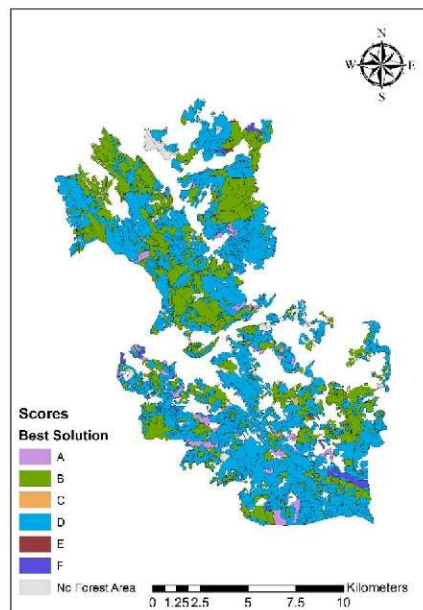


Figure 8. Best solution (A to F from Pareto frontier) for each stand, based on NetWeaver scores for each solution from the NetWeaver model (Figure 7).

4. Discussion

The present study demonstrates how knowledge-based decision support approaches encapsulated in the EMDS can be used to complement the multicriteria decision methods within the Pareto frontiers tool of SADfLOR, when the two DSS are employed in a simple collaborative way. Importantly, no additional programming was required because the two EMDS components, CDP and NetWeaver, both received outputs more or less directly from SADfLOR, with only minimal data processing needed for data exchange between the two systems. To briefly summarize the analytical steps used in this study, we first obtained the six nondominated solutions from the multiple-criteria Pareto frontiers approach in SADfLOR (Figure 3); next, an aspatial MCDA analysis with CDP was conducted to assess the aggregate performance of Pareto solutions A–F over all stands for the 90-year planning horizon with respect to delivery of ecosystem services (Figure 4), and; finally, a NetWeaver logical model version of the CDP model (Figure 6) was run in the EMDS system to assess the performance of the Pareto solutions at the scale of individual stands (Figures 6 and 7).

Pareto frontier applications have been used to study various forestry and natural resources phenomena related to several ecosystem services and forest management and planning. Authors in Reference [26] developed a Pareto frontier approach to assess trade-offs between timber-related criteria and spatial conditions correlated to other ecosystem services. Authors in Reference [27] used a production possibility frontier-based approach to evaluate the effects of bioenergy production on timber production potential and biodiversity. SADfLOR was built from forest ecosystem decision support system architectures [15–17] to evolve a Pareto frontier module that encapsulates the Feasible Goals Method/Interactive Decision Maps technique for interactive visualization of the web-based Pareto frontier [23,28]. Former developments of this multiple-criteria approach included the analysis of trade-offs between cork- and timber-related products at the regional level [22] and the analysis of trade-offs between timber-related products and a wide range of nonwood forest products [18] and regulatory services [29] at the landscape level.

The multiple-criteria method was developed further by this research to include three wood products and a subset of other ecosystem services (e.g., biodiversity, average carbon stored). Moreover, its collaborative planning functionality [18] was enhanced by the combination with other decision support approaches encapsulated in EMDS.

When there is only one decision-maker, or a group of decision-makers with similar preferences, the choice of only a single point on the Pareto frontier may be relatively easy. Nevertheless, in contexts characterized by multiple decision-makers, this may no longer be the case. Further negotiation may be needed to achieve a consensual solution. In this research, we have emulated such a situation where various (groups of) decision-makers with different preferences identify several optimal (nondominated) solutions in the criteria space (SADfLOR; Figure 3). So, the follow-on application of the classical aspatial strategic decision model in CDP (Figure 4) was used to elicit weights assigned by decision-makers to the ecosystem services and extend the analysis to compare the performance of six alternative Pareto solutions with respect to these preferences and the corresponding provisioning of ecosystem services (Figure 5). Although the CDP model in our study was relatively small and simple, being limited to consideration of a few provisioning services, the approach is readily extendible to more complex models that also consider supporting, cultural, and regulating services.

In this study, for demonstration purposes, the CDP and NetWeaver analyses were each conducted with a single model. More realistically, the present work could be extended to account for different weighting preferences among stakeholder groups. For example, Delphi methods could be used in conjunction with the CDP model structure to distinguish weighting preferences among a few to several stakeholder groups. With the groups being identified, the landscape of the whole study area could be partitioned according to the stakeholder groups and customized analyses run for each stakeholder group. It might also be of interest to the full group of all landowners in the association to reassemble the separate maps of outcomes from NetWeaver into a single composite map. This is easy to do in EMDS.

Finally, this study demonstrated the collaborative application of the SADfLOR and EMDS systems, but this collaboration required a modest amount of human intervention in terms of moving data between the systems, so an interesting question to pose is, “Is it feasible to automate the interoperability of the two systems?” The answer is a qualified yes. The EMDS system was rearchitected between 2012 and 2015, and is now built on the Microsoft Windows Workflow Foundation [30]. As a result, it is now relatively easy to integrate new analytical components into EMDS, albeit with a moderate amount of coding still required. For example, two new analytical engines were added into the EMDS architecture in the past year to support Bayesian network processing and Prolog-based decision trees. However, in the next year or two, EMDS will also integrate an open-source workflow editor, such as Trident [31], which will greatly simplify the task of integrating third-party analytical components into its architecture [32]. It is probably fair to say that open architecture DSS supported by workflow engines that simplify extensibility of DSS are the way of the future in continuing DSS development for environmental analysis and planning.

5. Conclusions

The provision of a wide range of ecosystem services requires a landscape-level management planning approach that may integrate temporal and spatial interactions between stand level management options. Nevertheless, landscape-level management planning often requires the negotiation of ecosystem services target values and corresponding management plans. This is complicated in contexts characterized by multiple stakeholders with diverse preferences. In this manuscript we demonstrated the potential of the combination of Pareto frontiers approaches within SADfLOR and EMDS decision modules to strengthen the collaborative planning process and to support the negotiation needed to reach a consensual solution.

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The development of wSADfLOR represented the first challenge. In fact, this task required the most time and effort on my part during the whole four-year project. The wSADfLOR was created and developed with the purpose of responding to the following research question: Is it possible to develop a web-based forest resources decision support system that improves simulation processes with the help of user-friendly interfaces and multi-criteria decision methods and tools, enabling decision makers to feel more comfortable and confident with their decisions on bundles of ecosystem services?

At present the wSADfLOR is a web-based decision support system dedicated to forest and natural resources ecosystem services and products. It includes modules for information management that interact with the entire system; simulation, forest management and planning; decision making with a Pareto frontier tool for trade-off analysis among ecosystem services and products; and data analysis of bundles of ecosystem services chosen by decision makers. The collaboration and involvement of stakeholders and the academic community in the development and improvement of this decision support system has proved vital.

The wSADfLOR was tested by a group of 18 stakeholders and decision makers through applying it to a real forest case study area. The group of stakeholders testing wSADfLOR with the involvement of four researchers completed a questionnaire on the ease of using wSADfLOR and its usefulness. The stakeholders expressed neutral opinions about the user-friendliness of interacting with maps and inventory data, the design of management alternatives, and the use of Pareto frontiers. However, they revealed positive responses to the creation of management plans, the overall usefulness of the system, and the analyzing management strategies. The system was evaluated with very strong positive responses for the usefulness of maps and inventory data, the process of generating management alternatives, the management of a property, analyzing strategies, and efficiency in forest management. The respondents also expressed interest in participating in the development of wSADfLOR applications. Based on the open question, we can conclude that some stakeholders were interested in receiving a user guide for wSADfLOR and further training sessions regarding its decision tools.

Taking advantage of the work developed to improve the versions of the IDM included in wSADfLOR, and showing the trade-off analysis between various criteria, an approach to build Pareto frontiers based on web graphical user interfaces (wGUI) was developed. For this special problem, the research question was: Is it possible to develop a web-based version of a FGOAL Pareto frontiers tool developed in C++ by Professor Vladimir Bushenkov?

Every time we develop an improved new version, it will be integrated in wSADfLOR. The second article focuses on this decision tool, which is valuable for forestry decision makers and other actors (users) facing a multi-criteria problem that can be expressed as a linear programming model written in a flat file (.lp extension), and that can be interpreted by CPLEX (or GLPK). This approach was built to make available an online version that represents Pareto frontiers. Given a point selected by a decision maker (user) on the IDM, it returns the closest solution in Pareto frontiers (efficient points). This web-based tool can provide an almost real-time solution to a (forest) management problem.

Based on these works concerning the bundles of ecosystem services rooted in the solutions chosen by different (groups of) decision makers who do not agree on the composition of bundles, a methodology for them to follow in order to obtain a consensual solution for the strategic forest management problem was suggested. Therefore, this third work was developed to answer the following research question: Is it possible to combine two DSSs (wSADfLOR and EMDS) to build a consensual solution for managing a forest area when the decision makers have distinct solutions for the composition of the bundle of ecosystem services to be delivered in the planning horizon?

The landscape-level management planning approach described in the third article involves a hybrid system fusing wSADfLOR and EMDS (CDP and NetWeaver), and integrating temporal and spatial interactions between stand-level management options. Thus, the bundles of ecosystem services (solutions) obtained from the Pareto frontier tool included in wSADfLOR are first evaluated by the CDP model. The CDP model scores and prioritizes the solutions, before their prescriptions are scored according to a fuzzy logic model with NetWeaver and are assigned to the strategic plan, which maximizes the prescriptions' scores for each management unit.

This methodology demonstrated the potential of combining both DSS (wSADfLOR and EMDS) to improve the collaborative planning process. This mixed approach solves the problem when we have various nonconsensual solutions for the strategic forest management plan, because it introduces a methodology that evaluates and compares all solutions and suggests a unique solution based on the best scored prescriptions for each management unit.

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