Visual Communication of
ECOSYSTEM SERVICES

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VISUAL COMMUNICATION OF ECOSYSTEM SERVICES

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“The two words ‘information’ and ‘communication’ are often used interchangeably,
but they signify quite different things.
Information is giving out; communication is getting through.”

Sydney J. Harris
*September 14th, 1917, † December 8th, 1986

Summary

The visualization and communication of environmental issues is challenging because of the need for a mutual understanding of information: Stakeholders expect to read and understand information while bringing in their opinions, experience, and expertise when assessing environmental changes. The pressure on the world ecosystem has changed dramatically in the last century. Globalization and the growing global population with rapidly changing consumption patterns of food, mobility and energy are exerting ever-increasing pressure on earth's ecosystems and their life-supporting services (EEA, 2015). The ecosystem services (ES) concept provides systematic information on the various services provided by ecosystems and thus has enabled communicating trade-offs between them—e.g., provisioning vs. regulating services under various development options. This can help stakeholders define their management strategies and finally ensure the sustainable management of ecosystems. Furthermore, the systematic categorization of ES offers an interface for various disciplines and links the expertise of a broad user group. The ES concept can thus serve as a common information ground and as a communication interface between heterogeneous user groups. Nevertheless, how to provide information most effectively for different purposes, applications, situations, and different types of users is an open question.

The goal of this Ph.D. project was to identify and investigate ES representations required by users and their implementation in decision support systems (DSSs) in order to enhance their usability and effective communication. To deal with these aspects, the thesis explicitly addressed the identification of the required and practice-relevant ES information types to test their usability and develop DSS components. These objectives were approached via three first (*Paper I-III*) and two co-authored papers (*Appendix A, C*), as well two conference proceedings (*Appendix B, D*), all completed during the course of this project.

In *Paper I*, the user requirements for ES information were identified by a demand analysis conducted via an online survey published on the social media channels of the global ES community. This demand analysis was designed as a requirements engineering approach to identify relevant types of representation, display scales for the various functions and situations in application by exploring the users' backgrounds. The compiled data were then statistically analyzed and the results were found to describe five main components of representation types and their specific functions in application, including (1) 3D landscape visualizations, which are generally used for analyzing and exploring ES-related information; (2) texts or text abstracts to support communication and discussions; (3) thematic 2D map representations for scenario development in public application; (4) abstract 3D landscape visualizations for estimations in group application; and (5) charts and tables in combi-

nation with thematic 2D map representations for analysis. This part of the research also highlighted the heterogeneous demands of users for ES information, according to the various purposes of its application. This study demonstrated the advantages of requirements engineering approaches in designing supportive ES information provision for DSS implementation. The results also emphasized the need for improvements in ES information provision and processing, and its potential failings in terms of the operationalization of the EU's Biodiversity Strategy 2020.

In order to further understand which representation and display types are needed for designing a DSS for supporting ES communication, an experimental study was designed as a *usability* test using an eye-tracking approach (*Paper II*). Here, the participants were assigned various tasks and questions related to applying a DSS prototype. The study results showed significant differences between DSS users. Their preferred representation types differed in terms of specific tasks and the application of the provided ES information. These effects were further influenced by their connection to the case study region. Furthermore, the results showed that these differences in user behaviors and characteristics affected cognitive processes and, therefore, task fulfillment and answering, as well decision-making strategies. These detailed insights into the interactions and effects of a DSS application for heterogeneous users underlined the significance of how ES information is provided.

Based on the findings from the first two papers, a *toolkit* providing generic and user-tailored ES information was developed (*Paper III*). This "LANDSCAPEization" toolkit allows users to link spatial data, e.g., land use patterns according to the land use types with their specific landscape elements for visualizing future landscapes. In this case, ES information and other indicator values can be directly linked to land use or landscape elements. Therefore, the effects of future landscape changes in terms of changes in land use patterns can be directly displayed by landscape visualization and ES and/or indicators. This novel and generic web-based 3D landscape visualization approach enables users to interactively investigate ES tradeoffs and their effect on landscape aesthetics. In addition, the developed toolkit includes participative GIS functionalities that open up novel possibilities in the mapping and evaluation of cultural ecosystem services. These functionalities allow users to map or rate specific sites or landscape elements according to, for example, their cultural values. The resulting toolkit allows an integral assessment of ES for decision making and thereby provides a customized DSS whereby the idea of ES as a common communication interface is implemented.

Four additional publications presented in *Appendix A, B, C, D* are also included in this thesis, since they are related to or contain the important findings of this thesis.

This thesis is positioned at the interface between visualization methods for spatial

information (e.g., 3D landscape visualizations) and the relevance of communications of ES within spatial planning with the development of methodic workflows for ES communication. The new insights gained from this research lead to recommendations that can support ES information provision and communication and DSS development.

As part of the interdisciplinary 7th framework EU OPERAs (Operational Potential of Ecosystem Research Application) and the National Research Project NRP68 OPSOL entitled, “Sustainable Use of Soil as a Resource,” the achievements of this Ph.D. project involve improving the communication strategies of ES in order to provide suitable information for specific user applications.

Zusammenfassung

Die Visualisierung und Kommunikation von Umwelt-Themen, ist aufgrund der Erfordernis eines gemeinsamen Verständnisses sehr herausfordernd: Stakeholder erwarten, dass sie Information lesen und verstehen können, um somit ihre Meinung, Erfahrung und Expertise zu einer Bewertung der Umweltveränderungen einbringen zu können. Im letzten Jahrhundert, hat sich der Druck auf die Ökosysteme unserer Erde dramatisch erhöht. Die Globalisierung und die zunehmende Weltbevölkerung mit ihrem rasch wandelnden Konsumverhalten für Nahrungsmittel, Mobilität und Energie, verstärken den bereits existierenden Druck auf die Ökosysteme und deren lebenserhaltenden Dienste zusätzlich (EEA, 2015). Das Konzept der Ökosystemleistungen (ÖSL) erlaubt es systematische Information über die verschiedenartigen Leistungen, welche durch die Ökosysteme bereitgestellt werden, verfügbar zu machen und ermöglicht somit, deren Zielkonflikte kommunizieren zu können - z.B. zwischen versorgenden und regulierenden ÖSL unter Berücksichtigung verschiedener Entwicklungsoptionen. Dies kann Stakeholder helfen, Managementstrategien zu entwickeln und somit ein nachhaltiges Management der Ökosysteme zu gewährleisten. Des Weiteren öffnet ein solche systematische Kategorisierung der ÖSL eine Schnittstelle zu verschiedenen Disziplinen, wodurch verschiedenste Expertisen der Nutzergruppe verknüpft werden können. Das ÖSL Konzept kann hierdurch als gemeinsame Informationsbasis und als Kommunikationsschnittstelle zwischen heterogenen Nutzergruppen fungieren. Wie Informationen für diverse Zwecke, Anwendungen, Situationen und verschiedene Nutzer am effektivsten bereitgestellt werden können, bleibt dennoch eine offene Frage.

Das Ziel dieser Doktorarbeit war es, die Anforderungen an Darstellungstypen zur Informationsbereitstellung über ÖSL, welche von Nutzern benötigt werden, zu identifizieren und zu untersuchen und diese dann in entscheidungsunterstützende Systeme zu integrieren, um die Nutzbarkeit solcher Systeme zu steigern, sowie eine effektive Kommunikation zu ermöglichen. Um diesen Aspekten gerecht zu werden, wurde die Doktorarbeit explizit auf die Identifikation von benötigten und zugleich praxisrelevanten Darstellungstypen ausgerichtet, um deren Nutzbarkeit zu überprüfen und darauf aufbauend, Komponenten für entscheidungsunterstützende Systeme zu entwickeln. Diese Ziele wurden in drei Erst- (*Paper I-III*) und zwei Co-Autor-Publikationen (*Appendix A, C*), sowie zwei Konferenzbeiträge (*Appendix B, D*) im Rahmen dieser Dissertation beschrieben.

In der ersten Publikation (*Paper I*) wurden Nutzeranforderungen bezüglich ÖSL Informationen mittels einer Anforderungsanalyse identifiziert, welche als Onlineumfrage via sozialem Netzwerk weltweit verbreitet wurde. Die Anforderungsanalyse wurde auf Grundlage von “requirements engineering” Ansätzen entwickelt, um relevante Darstellungstypen, Darstellungsmassstäbe für die verschiedenen Anwendungsfunktionen und –Situati

onen unter der Berücksichtigung der Hintergründe potentieller Nutzer herauszufinden. Die Resultate der statistisch ausgewerteten Daten, beschreiben fünf Hauptkomponenten von Darstellungstypen mit ihren spezifischen Anwendungsfunktionen: (1) 3D Landschaftsvisualisierungen, welche generell für die Analyse und das Erkunden von ÖSL Information verlangt werden; (2) Texte oder Kurzbeschreibungen, welche die Kommunikation und Diskussion unterstützen; (3) thematische 2D Kartendarstellungen, zur Entwicklung von Szenarien in öffentlichen Situationen; (4) abstrakte 3D Landschaftsvisualisierungen, für Abschätzungen in Gruppensituationen; und (5) Diagramme und Tabellen in Kombination mit thematischen 2D Kartendarstellungen für Analysen. Dieser Teil der Forschung hebt auch die Verschiedenartigkeit der Anforderungen der Nutzer, gemäss verschiedener Zwecke und Anwendungssituationen für ÖSL Informationen hervor. Die Studie hat die Vorteile von "requirements engineering" Ansätze für das Bereitstellen und Implementieren von hilfreicher ÖSL Information in entscheidungsunterstützenden Systemen aufgezeigt. Die Resultate betonen ebenfalls den Verbesserungsbedarf für die Bereitstellung wie auch Aufbereitung derartiger Information und das potentielle Risiko einer misslingenden Operationalisierung der EU Biodiversitätsstrategie 2020.

Um darüber hinaus verstehen zu können, welche Darstellungs- und Anzeigetypen es bedarf, damit ein entscheidungsunterstützendes System die erfolgreiche Kommunikation von ÖSL Information ermöglicht, wurde eine Nutzbarkeitsstudie auf Grundlage eines "Eye-Tracking" Ansatzes entwickelt (*Paper II*). Die Teilnehmer wurden mit verschiedenen Aufgaben sowie Fragen bezüglich der Anwendung eines Prototyps eines entscheidungsunterstützenden Systems konfrontiert. Die Ergebnisse dieser Studie zeigten signifikante Unterschiede zwischen den verschiedenen Nutzergruppen. Ihre Vorzüge in Sachen Darstellungstypen unterschieden sich je nach Aufgabe als auch nach der Anwendung der bereitgestellten Informationen. Auch eine Verbindung der Nutzer zum untersuchten Gebiet hat diese Effekte weiter beeinflusst. Des Weiteren zeigten die Resultate, dass die Unterschiede im Verhalten und im Charakter der Teilnehmer sich auf die kognitiven Prozesse und somit auch auf die Bearbeitung und Beantwortung der Aufgaben, als auch auf die Strategie zur Entscheidungsfindung auswirkten. Diese detaillierten Einblicke in die Interaktionen und Effekte der Anwendung eines entscheidungsunterstützenden Systems für heterogene Nutzer, unterstreicht die Wichtigkeit der Darstellungsart von ÖSL Informationen.

Basierend auf den Erkenntnissen der zwei Studien, wurde eine Software für eine generische und nutzerorientierte Darstellung von ÖSL Information entwickelt (*Paper III*). Dieses Tool namens "LANDSCAPEization" ermöglicht den Nutzern räumliche Datensätze, z.B. Landnutzungsmuster mit deren Landnutzungstypen und ihren spezifischen Landschaftselementen zu verknüpfen, um so zukünftige Landschaften visualisieren zu können. In diesem Zusammenhang können Informationen über ÖSL und andere Indikatoren direkt mit Landnutzungstypen oder

Landschaftselementen verknüpft werden. Dadurch können Auswirkungen von zukünftigen Landschaftsveränderungen, ausgelöst durch eine veränderte Landnutzung, direkt aufgezeigt, visualisiert und zusammen mit Informationen über ÖSL und/oder anderen Indikatoren wiedergegeben werden. Diese neuartige und zugleich generische Methode einer web-basierten 3D Landschaftsvisualisierung, ermöglicht Nutzern interaktiv Zielkonflikte bezüglich ÖSL sowie ästhetische Auswirkungen auf die Landschaft zu untersuchen. Zusätzlich erlaubt die entwickelte Applikation partizipative GIS Funktionalitäten, welche neue Möglichkeiten in der Kartierung und Bewertung von kulturellen ÖSL eröffnet. Diese Funktionalitäten erlauben den Nutzern spezifische Orte oder Landschaftselemente, beispielsweise nach ihren kulturellen Werten, zu kartieren und zu bewerten. Die entstandene Applikation ermöglicht eine integrale Beurteilung von ÖSL und stellt somit ein individuell anpassbares entscheidungsunterstützendes System bereit, wobei der Grundgedanke von, das ÖSL Konzept als gemeinsame Kommunikationsschnittstelle umgesetzt wurde.

Vier zusätzliche Publikationen sind im Anhang *(Appendix A, B, C, D*) dieser Arbeit zu finden, welche weitere, zu diesem Thema relevante Erkenntnisse bereitstellen.

Mit der thematischen Schnittstelle zwischen Methoden zur Visualisierung räumlicher Information (z.B. 3D Landschaftsvisualisierungen) und der Bedeutung von Kommunikation von ÖSL in der Raumplanung, wurden mit dieser Dissertation wichtige Erkenntnisse gewonnen, sowie neue methodische Abläufe entwickelt. Diese neuen Erkenntnisse aus dieser Forschung können dazu beitragen, Empfehlungen für eine effektive Bereitstellung von ÖSL Information weiterzuentwickeln, sowie deren Implementierung in entscheidungsunterstützende Systeme nachhaltig zu verbessern.

Als Teil des interdisziplinären 7th framework EU OPERAs Projektes (Operational Potential of Ecosystem Research Application) und dem Nationalen Forschungsprojekt NFP68 OPSOL zum Thema “Nachhaltige Nutzung der Ressource Boden” konnte mit den Erkenntnissen aus dieser Arbeit, zu Verbesserungen von Kommunikationstrategien hinsichtlich ÖSL und der Bereitstellung von nachhaltiger Information für spezifische Nutzergruppen innerhalb dieser Projekten beigetragen werden.

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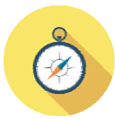


1. Chapter I: Introduction

1.1. General introduction

In order to sensitize people to the consequences of ecosystem changes with regard to human well-being and to improve conservation and the sustainable use of ecosystems, effective communication that illustrates long-term and indirect environmental impact is essential. A prerequisite for effectiveness in communication is that the user's demands and requirements related to information are known. Based on such knowledge, information can be represented and visualized in an understandable and readable form.

By incorporating perceptions of values in its scientific scope, the ecosystem services (ES) concept has been promoted to increase public interest in biodiversity conservation and to integrate the value of the services provided by nature in decision making (Braat and de Groot, 2012; Termorshuizen and Opdam, 2009). Decision support systems (DSSs) that integrate ES in landscape and urban planning have been shown to support the sustainable management of ecosystems (Geertman et al., 2013; Deal et al., 2013; Bagstad et al., 2013; Grêt-Regamey et al., 2013, 2016). "Achieving a more sustainable future […] necessitates a departure from the traditional approach to planning and decision-making to take into account the long-term impact of planning and infrastructure investment decisions in social, economic and environmental terms" (Deal et al., 2013). Designing such a DSS requires thus the identification of the existing state of ecosystems and the potential services they provide, as well as the identification and understanding of how changes will affect them (Deal et al., 2013). The transformation of data into readable information is, however, highly challenging and requires effective visualization and communication techniques (Deal et al., 2013).

Besides information about the provisioning, regulating and supporting ES, changes in cultural ES (CES) also need to be considered when assessing and communicating the consequences of changes in ecosystems: CES encompass aesthetic issues related to ecosystem changes. However, visualization approaches that provide decision-supportive information for ES assessments in a comprehensive way are not yet available. Furthermore, recommendations or approaches to implement and visualize ES trade-offs within a DSS are missing. In particular, the current technical workflows for linking different types of representations and generating realistic 3D landscape visualizations for assessing CES are not generic enough for implementation in web-based DSS or for supporting the transparency and credibility of the provided information to allow users to better understand trade-offs in various ES actions. Finally, the heterogeneous demand for ES information representations is often disregarded and results in failure in communication. Thus, technical approaches for providing and linking different kinds of ES representations need to be developed. This also requires an adequate elicitation method for identifying user needs for ES information in order to process and provide comprehensive ES decision-supportive tools.

1.2. Research background

"It is becoming increasingly clear that population growth and economic development are leading to rapid changes in our global ecosystems" (MEA, 2005). Anthropogenic activities have threatened major ecosystems and degraded many landscapes from the global to the local scale (e.g., Malmqvist and Rundle, 2002; Folke and Holling, 1996; Cole and Landres, 1996; Halpern et al., 2007; Wilkinson, 1999). The resulting consequences of ecosystem change for human well-being need to be assessed to promote actions that enhance conservation and the sustainable use of ecosystems, so that the services that underpin all aspects of human life can continue. For example, in urban areas, the sealing of soil surface is predicted to affect water infiltration and decrease groundwater recharge (Faber and Wensem, 2012). Moreover, in rural mountainous areas, deforestation will potentially affect the stability of slopes and decrease natural protection against gravitational natural hazards (Grêt-Regamey et al., 2008). Hence, sustainable development is vitally dependent on the improved management of our planet's ecosystems. To make sustainable decisions, we have to integrate social, economic, and environmental factors into decision making, which can help define the long-term impact of planning and investment decisions (Deal et al., 2013; Deal et al., 2012).

The concept of ES was developed with the goal of allowing better consideration of the value of the services provided by nature in decision making (e.g., Farley, 2008; Daily et al., 2009; TEEB, 2010; MEA, 2005). "ES are the benefits people obtain from ecosystems. These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, food, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling" (MEA, 2005).

The concept of ES is proposed to provide the basis for a common language for communicating the value of ecosystems and the goods and services they provide (e.g., Brauman et al., 2014; Granek et al., 2010). However, while the current methods in ES mapping and modeling aim at generating spatial and temporal ES information on the sub-regional to global scale driven by currently available data (Schägner et al., 2013), information on ES supply and demand cannot be fully applied in actual planning processes due to the incompatibility of the resolution of the scales (Ahern et al., 2014; Colding, 2011). There is, however, an urgent need to link scientific achievements to practice through operational methods and instruments in order to facilitate the integration of ES values into societal decision making (Ash et al., 2010; Goldstein et al., 2012). Such operationalization efforts should include trade-off assessments in order to manage the multi-functional use of the landscape in a sustainable way (de Groot et al., 2010). For example, the increasing demand for living space through population growth requires the use of land that is currently used for agricultural production or provides crucial recreational or cultural services. In order to make sound decisions that balance all these aspects, trade-offs are needed between economic interests—such as those of farmers—and the social and cultural values of citizens, as well as the economic pressures of creating living spaces by means of private investment. This balance can be achieved by means of a participatory planning approach that can support these multi-faceted concerns, for example, by ensuring that an intervention will have more credibility in the community, by bringing a broader range of people to the planning process or by providing access to a broader range of perspectives and ideas. It can also address the concerns raised by avoiding pitfalls caused by ignorance of the realities of the community (Holt et al., 2016). Thus, tools that support sustainable decision making should include options for application in participatory processes and ES information that is comprehensible to all stakeholders. Geographic information system (GIS)-based 3D landscape visualizations have proven their worth as powerful tools for communicating spatial information to groups of heterogeneous stakeholders (Grêt-Regamey et al., 2013). In particular, 3D landscape visualizations have been found to be especially suitable for communicating and assessing cultural ES, such as landscape aesthetics (Daniel et al., 2012).

1.3. The present doctoral thesis

The goal of this Ph.D. thesis is, therefore, to develop (1) a demand analysis based on requirements engineering methods in order to identify user demands for ES information. The identified demands and the components of ES representations shall then be further investigated by usability testing. (2) This thesis aims to identify the effects on user behavior while perceiving ES information, and therefore, the potential influence on cognitive and decision-making processes. The results of (1) and (2) shall be used as a framework to (3) design a generic toolkit for visualizing ES information by relevant types of representations in order to embed ES information in a DSS for heterogeneous user groups. Novel workflows for creating generic realistic 3D landscape visualizations based on the above will help provide CES information to support a trade-off assessment of all categories of ES. Finally, applying the developed tools and workflows in various stakeholder workshops will lead to (4) practical recommendations on how to use DSS and the usability of its single components (e.g., representation types and the visualization approach) in the planning process.

1.3.1. Major research questions

In order to allow better integration of ES into decision making, a DSS that is capable of providing GIS-based visualizations of ES to stakeholders in actual planning situations is required. This Ph.D. project thus aims to contribute toward the development of such DSS components and the testing of novel visualization and information technologies by addressing the following research questions:

Research question 1 (Paper I):

What are the requirements and demands for ES information representation (by type, spatial, and temporal scale) according to the purpose of the application (function in application)? Are there differences/commonalities between the demands of specific user groups?

Hypothesis: The demands for ES information vary according to user characteristics (e.g., expertise and background) and the application of the provided ES information. The varied settings for user demands are crucial for providing applicable and supportive ES information.

Research question 2 (Paper II):

Although identifying user needs by demand analysis predefines the theoretical requirements, it is unclear how these support practical application. How will user preferences for ES information be practically applied and in what way do they support users? Does the support of preferred components vary between users with connections to the case study region? How do these potential differences in the use of ES information affect users' cognition processes, reasoning, and, therefore, decision making?

Hypothesis: Depending on the context in which users apply the ES information, the preferences for ES representation and display type (e.g., display scale) change. These preferences potentially vary further among users due to their different characteristics, especially if they have a connection to the case study region. This user behavior further affects cognitive processes and thus consequently impacts decision making, which underlines the power of DSS-integrated ES information.

Research question 3 (Paper III):

No tool or even approach exists that allows the generic production of ES information based on land use patterns with their constituted land use types and landscape elements to produce realistic landscape visualizations. However, such an approach is required to enable an integral trade-off assessment among all ES. Therefore, how can a technical workflow support such a generic real-time trade-off assessment of ES?

Hypothesis: For a comprehensive ES assessment among all ES categories – i.e. including CES in trade-off assessments—a form of visualization workflow is required which allows the transformation of ES data to useful and readable information. The visualization approach can be used for this purpose, but the landscape qualities also need to be considered according to land use type, landscape elements and sites, as these provide cultural values and therefore need to be identifiable and assessable by DSS users.

1.3.2. Procedures and methods

The research in this thesis was structured according to the three research questions described above. In Paper I, a user demand analysis was developed to query detailed user needs for ES information and its representations. After important user requirements and DSS components were identified and defined, a framework for a web-based DSS for ES information and assessment of different spatial scales was designed (Paper II). Then, the usability of the required DSS components was tested by a DSS prototype. In Paper III, a technical workflow and toolkit for realistic 3D landscape visualizations based on ES information for DSS implementation was developed and especially tailored for CES information provision. Through this constitutive approach, the outcomes of these three questions were evaluated with regard to their practical relevance by applying them in various workshop situations within the scope of selected projects.

Paper I (research question 1):

In order to identify user requirements for decision-supportive ES information and the related types of representation, a user demand analysis was developed. The structure of the user demand analysis was based on requirements engineering methods to query heterogeneous user demands via a systematic approach (Aurum and Wohlin, 2005; Zerweck and Gehlhaar, 2009; Krcmar, 2013). Such systematic surveys allow researchers to sort and investigate the collected demands in order to categorize the need for managing, prioritizing and structuring development processes, and linking them based on further systematic methods, such as usability tests (Grünbacher and Seyff, 2005; Berander and Andrews, 2005; Jönsson and Lindvall, 2005). The survey was conducted in the form of a web-based questionnaire (www.soscisurvey.de) that provided potential DSS users or ES information recipients with easy online access. The survey results helped to evaluate the required ES information and DSS functionalities to bridge the implementation gap and ensure practical relevance.

Paper II (research question 2):

After identifying the project or case study's specific demands in relation to potential DSS users (Paper I), the ES information was prepared in order to generate the required representation and display types for a DSS prototype. Information was processed in the form of different representation types to investigate which combinations of visualization types facilitated a better understanding of various ES provided under different scenarios. Depending on the nature of the functions of the applications (e.g., for decision making), different combinations were applied and linked in order to guarantee multiple functionality of the provided information in terms of communication, exploration, and analysis (Te Brömmelstroet, 2010; Van der Hoeven, 2009; Geertman, 2008; Wissen Hayek et al., 2012b; Wissen Hayek, 2011). The usability of the DSS prototype with its various components was tested by eye-tracking measurements in an experimental study design. Additionally, this evaluation required and provided information via a DSS prototype that showed how usable and effective the demand analysis was (Paper I).

Paper III (research question III):

In order to combine the different requirements for ES information and present this information at different requested temporal and spatial scales and with differing levels of detail, technical workflows were required and designed (Pensa et al., 2013). From a technical perspective, these workflows enable to generate different representation types for information on a single ES, whereby, for example, data loading could be reduced for a user-optimized web-based DSS with adoptable user interfaces. The resulting visualizations and combinations of representation and display types were implemented in a toolkit in order to enable generic DSS-embedded realistic landscape visualizations based on ES information. The current workflows for generating realistic visualizations are still not capable of directly retrieving ES information from an interactive web-based DSS. However, this representation type is especially valuable for assessing CES in terms of, for example, landscape aesthetics and the sense of place (Daniel and Meitner, 2001; Klein et al., 2012). With the design of technical workflows and the evaluation of proper combinations of representation and display types (Paper I and II), quantitative ES information was thus embedded in the user interface to allow weighting of all ES (Grêt-Regamey and Wissen Hayek, 2013). Procedurally realistic urban visualization approaches have recently been developed, and these techniques (e.g., ESRI CityEngine) depict the influence of CES on the visual impact of settlements. Approaches to visualization with a high level of realism linked to ES information for rural areas and areas where vegetation is predominant, however, are still unavailable, and current visualization approaches in this field are also unsuitable for web-based DSS implementation (Neuenschwander et al., 2012; Klein et al., 2012). Through this study's novel approach, a more generic real-time realistic landscape visualization workflow was developed, which can also support the assessment of CES and other indicators related to ES changes.

1.3.3. Overview of this thesis

The research questions are addressed in three main publications published in or submitted to peer-reviewed (ISI) journals (*Paper I*, *II, III*). In addition, two peer-reviewed journal papers (co-authored, see *Appendix A, C*) and two conference papers (*Appendix B, D*) have been included, since they provide important findings gained from this Ph.D. project.

Chaper II: Theoretical background

This chapter provides a brief overview and background information on the broad topics and state-of-the-art techniques which are addressed in the individually researched parts (*Chapter IV-VI*). This chapter also includes supplementary material on topics which are not addressed explicitly in this Ph.D. thesis but are, nonetheless, important for framing this research and providing a larger context.

Chapter III: Planning perspective

In this chapter a brief overview and background information is given on how topics of *Chapter II* are incorporated in spatial planning.

Chapter IV: The identification of user demands (Paper I)

In this chapter, a demand analysis is presented for exploring information gained through an online survey to identify user demands for ES information. The principal component analysis depicted how information requirements were highly heterogeneous among the respondents of this study. Five components describing these representation types can, however, be identified, depending on the application situation and the intended use of the ES information by the respondents. However, while certain representation types are function- and/or situation-specific, no representation type can be used as a panacea. A demand analysis, as presented in this chapter, can contribute to the definition of how ES information must be integrated into DSSs and how it needs to be designed to be decision supportive.

Chapter V: The usability of ES information (Paper II)

While the results of the demand analysis (*Chapter IV*) describe only theoretical needs, in this chapter's usability test, user demands were practically evaluated. To investigate and assess the usability of specific design features of an ES-based DSS prototype, an eye-tracking experiment was designed. The study was conducted with more than 100 participants who were split into two groups. The participants in both groups had a background in spatial planning, but differed in their connection to the case study region. The provided DSS prototype presented various GIS-based modeled land use scenarios driven by the revision of the spatial planning policy recently adopted in Switzerland that would have various effects on the ES of the region. The ES information was shown with additional land use indicators, as well as information about changes in the landscape aesthetics via landscape visualizations. The results show that there were significant differences among the participants in the way they perceived, interpreted, and used the information for ES-based decision-making tasks. Further, critical key factors in defining the types of information representations that influence perception and cognitive processes were identified. In summary, the results of the study provide design recommendations for representing ES information based on its intended use and identify critical representation features that could potentially influence the perception of ES information.

Chapter VI: LANDSCAPEization: A toolkit for visualizing landscapes in ecosystem services assessments (Paper III)

In this chapter, the LANDSCAPEization toolkit is presented, which was developed based on the previous identified heterogeneous user demands and user behaviors in practical applications of ES information (*Paper I* and *Paper II*). The toolkit allows the visualization of and reporting on ES- and non-ES-related information. By allowing 3D visualizations of land use patterns in real time, the toolkit allows the communication of changes in the landscape and thus supports trade-off assessments between CES and other ES. Additionally, beside interactive functionalities for accessing ES- and non-ES-related information, the LANDSCAPEization toolkit also enables a participatory mapping and rating functionality for CES and thus offers an innovative approach to support integral ES-informed decision-making across all ES categories.

Chapter VII: Synthesis

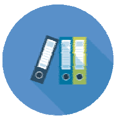
This chapter summarizes the conclusions of this Ph.D. thesis, highlights its scientific contributions, and explores future directions in the area of visualization and communication approaches for ES information.

Appendices A–D

The appendices provide additional publications (partially co-authored) presenting important findings gained in this Ph.D. project. I contributed to these papers primarily by developing the concepts of technical frameworks for the DSSs and the workflows for the production of landscape visualizations, and/or discussing the applied methods and results (*Appendix A, C*). The additional conference proceeding publications (*Appendix B, D*) relate to the technical requirements and practical applications of DSS development, landscape perception, and interactive 3D landscape visualizations, and outlines a technical framework for realistic landscape visualizations embedded in a web-based DSS.

1.3.4. The embedded projects

This doctoral thesis was embedded in the interdisciplinary 7^{th} framework EU OPERAs (Operational Potential of Ecosystem Research Application) and National Research Project NRP68 OPSOL under the topic “Sustainable Use of Soil as a Resource.” Both projects focused on different aspects of land use change under various policy instruments in the regions of Visp (Canton Valais, Switzerland) and Greifensee (Canton Zurich, Switzerland), with the aim of contributing to the development of adapted land use practices and innovative policy solutions (e.g., Celio et al., 2015; Brunner et al., 2016). These projects included researchers from multiple disciplinary backgrounds, including ecology, socio-economy, and political sciences. In terms of both projects, this Ph.D. study contributed to enhancing communication due to better ES information supply and DSS provision. With regard to the projects’ goals, the results of this Ph.D. study have improved the projects’ participative processes by providing supportive ES information with a project- and stakeholder-tailored DSS in order to support sustainable landscape development and integral ES assessment via consideration of CES.



2. Chapter II: Theoretical background

2.1. Ecosystem services concept

With the concept of ES (MEA, 2005), a systematic approach is provided that enables the categorization of services supplied by nature's ecosystems. In terms of categorization and classification, ES are divided into four groups: supporting services (e.g., nutrient cycling, soil formation), provisioning services (e.g., food, fresh water production), regulating services (e.g., climate, flood regulation), and cultural services (e.g., aesthetic, and recreational services) (see MEA, 2005). The mainstreaming of this concept, i.e., introducing it as a policy at the governmental level and in the private sector, has already started in Europe (e.g., the EU's Biodiversity Strategy to 2020) and all over the world (Schleyer et al., 2015; Greenhalgh and Hart, 2015; Schaefer et al., 2015). This initiation relates to the great expectations placed by practitioners, policy makers, and scientists alike on improving environmental policies and preventing biodiversity loss (Schleyer et al., 2015).

There is no doubt that the concept of ES, on account of its systematic clarity, helps us to understand, define, and conceptualize more clearly the links between human well-being and ecosystems, whereby communication in groups with interdisciplinary backgrounds and specially to lay persons can be enhanced. However, this systematic framework simultaneously has fostered counter-arguments, including criticism of the vagueness of its definitions and classifications, as well as its normative nature (Schröter et al., 2014).

Since Action 5 of the EU's Biodiversity Strategy 2020 and the calling upon EU Member States to map and assess the state of ecosystems and their services in their national territory by 2014 (MAES, 2014), a theoretical common ES information base for policy making within the EU has emerged. However, the systematics of the concept and its technical implementation are not in line with nature's complexity, as current mapping practice shows (e.g., Liquete et al., 2015). ES values are often laden with uncertainties because of a lack of knowledge and understanding of the biophysical processes underlying their provision, difficulty in the selection and definition of ES indicators, the coarseness of information related to land use and land cover data, difficulty in addressing the dynamics and scale issues easily, or technical issues such as inaccuracy of spatial data or their availability are limiting their uses (Liquete et al., 2015; MAES, 2014). These challenges limit the comparability of ES mapping outcomes due the use of different methods; this calls, therefore, for a more consistent but flexible approach (Grêt-Regamey et al., 2015). A tiered approach, as described by Grêt-Regamey et al. (2015), could ensure such standardization in order to provide a common ES information base across boundaries and scales. Furthermore, such an approach guarantees the inclusion of information relevant to decision makers at different levels.

With regard to ES indicator availability and quality, applying the ES concept to landscape planning and management seems to be extensive and complicated, so practitioners need to take a step forward to convince people of its potential usefulness (Albert et al., 2016; Wissen Hayek et al., 2016). Furthermore, the lack of data influences the usability and credibility of the ES concept due to missing indicators and, therefore, biased information provision, whereby its legitimacy and credibility are potentially affected (Wissen Hayek et al., 2016; Ruckelshaus et al., 2013). Especially in the case of CES, it is not clear how they can be identified or incorporated in DSSs. Because of their highly normative and subjective evaluation characteristics, CES need to be integrated using alternative approaches in order to allow for consideration of their actual social values. Currently, CES are not perfectly covered in ES research (La Rosa et al., 2016). Many of the available methods for providing CES information or indicators cannot be incorporated in planning, as the information provided is incomplete by focusing on single CES, or the information quality is limited by an incompatible or inappropriate scale. For example, CES consideration in urban planning is mostly limited to single services, such as recreational services (Albert et al., 2016; La Rosa et al., 2016; Wissen Hayek et al., 2016). However, provision of balanced information about all the relevant ES is important for decision making in terms of future sustainable landscape development. Therefore, it requires suitable representation types that display ES in a comprehensive way such that it supports communication and can be incorporated into landscape planning.

2.2. Communication and information transfer

Communication can be defined as information transfer by sender and receiver components, and the channel through which this information is transferred in signals (Shannon and Weaver, 1976). This can vary in terms of its transfer and information technology modality. However, its principle is universal and only signal processing, i.e., the technological method for transferring information by signal coding and recoding, varies according to media, besides the information type itself (e.g., text, picture, or video). Furthermore, for successful communication, the sender and receiver components need to be compatible with each other and, therefore, use the same signal processing method. This means that they both speak the same language based on a successful (re)interpretation or (re)coding of the transferred information (Ahlswede et al., 2006). The role of the sender and receiver can change via a feedback channel, but from a non-technological view, the transferred information still needs to be readable and understandable for the receiver.

The fundamental characteristics of information are that (1) the information has a function, (2) the information content is about an aspect of an issue that is relevant to the recipient, (3) a convention defines the meaning of communication, and (4) the information is linked to a medium (Bollmann and Koch, 2001). Available data is thus not information, but the information is the data that is received, perceived after selection, and filtered by the recipients (Doelker, 1999; Frey, 1999).

In this context, the provided information can affect various cognitions and therefore actions, due to individual selection and filtering by recipients. This influence of individual behaviors is a crucial aspect of the communication process and, thus, knowledge transfer. Through such a selection and filtering process, the transferred information content is potentially reduced and the actual function of communication can be influenced by the recipients' interpretation, which might lead to biased actions. This effect induced by individual behaviors is based on individual performance and cognition, which are defined by the encoding and perception of the provided information. Therefore, this defines a basic problem in communication processes as individuals differ in their characteristics, e.g., language, expertise, social, and cultural background (Fürst and Scholles, 2001; Diekmann, 2005; Bienert, 1998).

2.3. Decision making

A decision-making process requires a specific quality of information on which decisions will be based to enable decision makers to better understand the impact of their choices (Qudrat-Ullah et al., 2008). Complex decision making as described by Qudrat-Ullah et al. (2008) can be supported by providing a "what-if" scenario analysis opportunity to the decision makers. Through access to such scenario information by model outputs, decision makers can understand e.g., feedback processes, non-linear relationships between variables, and time delays in the performance of complex systems (Qudrat-Ullah et al., 2008). However, theoretical frameworks of such complexity can involve uncertainties. These uncertainties could either be related to incomplete or imprecise system variables (Bouyssou et al., 2009), or unknown system behaviors caused by unpredictable or fuzzy behaviors within a system, e.g., those created by the influence of multiple decision makers in a system as it is described in the game theory (e.g., Kelly, 2009).

The decision-making process itself can be mapped by a decision strategy that describes the procedures used by decision makers when facing a problematic situation (Bouyssou et al., 2009; Tversky, 1972; Montgomery, 1983; Montgomery and Svenson, 1976; Gigerenzer and Todd, 1999; Barthélemy and Mullet, 1992). However, the sequential process of decision making, in which alternative decisions are assessed and different decision rules are applied, is strongly related to information-processing strategies (Montgomery and Svenson, 1976). This synergistic relationship between processing of information, assessment of alternative decisions, and application of decision rules underlines the significance of information provision and further characterize its influence on decision making. Vessey (1991) and Vessey and Galleta (1991) describe this information processing while decision making and its effects on decision strategy with cognitive fit theories. These theories describe the evaluation and identification of relevant information by decision makers. Decision makers in general use information that fits their chain of thought. This can guide them to their particular cognitively fitting decision strategy (Vessey and Galleta, 1991).

However, as Bouyssou et al. (2009) outline in their overview of the history of decision theories, most theories relate to the decision-aiding process and are further framed by process's assumptions or goals. Nevertheless, several investigations have shown that the formulation of a decision problem and the presentation of scenarios affect the cognitive context of a decision process, which is fundamental for the final decision making. This challenge has been investigated in the prospect theory (Kahneman and Tversky, 1979; Tversky and Simonson, 1993; Tversky and Kahnemann, 1982).

Finally, the basic and individual framework of decision making is related to individual characteristics, such as beliefs, cognitive processes, and processing of the provided information. However, this framework can be affected by external influences, such as time pressures, hierarchical bondage, and non-anonymity, as well as extended system complexity involving e.g., mutual system influences due to the presence of multiple decision-making actors (Svenson and Maule, 1993; Qudrat-Ullah et al., 2008).

2.4. Requirements engineering

Requirements engineering approaches serve to define and/or work out the necessary features to support the achievement of a goal in a development process, as well as the management of the developmental stages (Hull et al., 2005; Rupp et al., 2014). Therefore, establishing these requirements can help focus on the development of a product by initially defining the problem's scope and then linking all subsequent developmental information to this. Requirements are the basis for every project as they define what stakeholders, users, customers, suppliers, developers, and businesses need and expect from a new product (Hull et al., 2005). However, these identified needs can be very heterogeneous, diverse, or even contrary (Sommerville and Sawyer, 1997; Hull et al., 2005). The challenge is, therefore, to manage these requirements by identifying the most relevant needs, without disregarding the others, through the implementation of a proper design, including trade-offs, to provide a satisfying solution for as many users as possible (Ruhe et al., 2003; Otto and Antonsson, 1991; Laplante, 2009; Hull et al., 2005).

However, the success of such requirements engineering methods is related to the feedback of potential users. Therefore, reasons for the failure of requirements engineering approaches and developments (e.g., products) are multi-faceted and can be based on e.g., incomplete requirements, lack of user involvement, lack of resources, unrealistic expectations, and changing of requirements/specifications; the success factors, on the other hand, are e.g., user involvement, clear statements about requirements, realistic expectations (smaller milestones), and ownership (Hull et al., 2005; Lawrence et al., 2001; Burnay et al., 2014).

Requirements engineering approaches support the systematic management of development due their scalability. This scalability allows the application of the various approaches on different scales, levels and stages to identify requirements and test them in a suitable environment for optimized design matching (Pernstål et al., 2015). For example, stakeholder requirements can be tested by acceptance testing of the final product; system requirements can be tested via system tests; subsystem requirements can be tested through an integration test; and component requirements can be finally tested using component tests (Burnay et al., 2014; Hull et al., 2005). Such scalability allows for the provision of a solid level of requirement details, so the features or components of a product can be customized.

Additionally, various methodologies (de Gea et al., 2012), such as demand analyses, interviews, prototyping, card sorting, brainstorming, eye-tracking, and usability testing, are useful for identifying requirements in detail; designing or improving components, features or products; and for further evaluating their usability with the support of traceability and, therefore, reasoning why these features or components were integrated in a product (Laplante, 2009; Valderas and Pelechano, 2009; Burnay et al., 2014; Maté and Trujillo, 2012; Spencer, 2009; Lipp, 1986; Thomas, 1987; Dumas and Redish, 1999).

2.5. Landscape visualizations

The possibility of depicting future landscapes was first discussed in the early nineteenth century when Repton (1803) used representations for presenting landscape changes via a *before* and *after* view. Representation techniques and media have changed over the years—the initial methods were based on image compositions, sketches, perspective drawings, photomontages, and physical models (Rekittke and Paar, 2008; Lange, 2001), but improvements in computer technology and performance over the last century have led to the use of digital photomontages, animations, interactive worlds, virtual globes, and 3D visualizations for the presentation of future landscapes (Bishop, 2015). These developments and improvements in landscape representation allow for high levels of detail and realism, as well as interactivity, and present new possibilities for the communication of landscape changes and their impact, as is especially required in spatial planning (e.g., Grêt-Regamey et al., 2013; Klein et al., 2012; Bishop and Stock, 2010; Lange, 2005; Stock et al., 2005; Wissen et al., 2008).

The establishment of GIS and, therefore, the availability of spatial data in many fields of administration, provides novel opportunities for the usability of landscape visualizations in spatial planning (e.g., Glaus et al., 2011; Wissen, 2009). By linking landscape elements represented by highly detailed 3D objects with GIS, a further step in landscape visualizations can be achieved with a high level of realism of spatial data (Griffon et al., 2011;

Lange, 2011; Wissen et al., 2008). Many studies have shown that landscape visualizations are a powerful tool for communicating landscape changes and their impact (e.g., Lovett et al., 2015; Pettit et al., 2011). In particular, landscape visualizations with a high level of realism can evoke emotional feelings in stakeholders (Daniel and Meitner, 2001; Sheppard, 2005; Maehr et al., 2015), which communicate landscape qualities in an interesting manner, such as landscape aesthetics and the sense of place, which are more difficult to invoke by abstract and cartographic representations, such as maps (e.g., van Zanten et al., 2016; Maehr et al., 2015; Grêt-Regamey et al., 2013; Griffon et al., 2011). These features allow the use of landscape visualizations as a common information base for an improved understanding of the landscape that also includes lay people's opinions and makes these insights visible and available for use in decision making (e.g., Kwan, 2015; Pettit et al., 2011; Lewis and Sheppard, 2005).

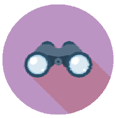
2.6. Decision support systems

Geertman et al. (2013) differentiate between planning support systems (PSS's), spatial decision support systems (SDSSs), and decision support systems (DSSs). Although all three system types focus on decision support, there exists a slight difference in their definitions. Originally, DSSs were defined by their role in short-term policy making. Moreover, SDSSs also include a spatial component and aim to support operational decision making, whereas PSS's aim at supporting strategic planning activities and the solution of long-term problems. PSS's also contain spatial information that is typically GIS-based and provides support for specific tasks (e.g., scenario planning).

In this thesis, DSS is defined as a general system that also contains information features, such as the SDSS definition of GIS-based information or functions of applications related to the PSS definition of the planning process. In this redefinition of DSS, the discussion of terms will not be the focus, as this thesis investigates all kinds of features and components in DSSs described by all three system type definitions. Additionally, this thesis includes the features and capabilities of public participation GIS (PGIS/PPGIS). This definition of GIS further describes features which support the involvement of the public in GIS applications, as they can be used for participative processes that stakeholders may request, for example, mapping or assessments functions (e.g., Brown and Fagerholm, 2015; Brown et al., 2014; Sieber, 2001).

Recent research (Wissen Hayek et al., 2016) has investigated important steps in creating a transdisciplinary process supporting DSS development, as some studies have pointed to a gap between the promised and actual usability of the provided DSS (McIntosh et al., 2008; te Brömmelstroet, 2009). In addition, to provide a system that increases usability and effective implementation, deep communication between developers and practitioners is required. Such communication supports the design of information and systems by translating information to improve mutual understanding and mediation concerning stakeholders' conflicting views on how to achieve saliency (relevance of information), legitimacy (fairly biased information), and credibility (adequacy of evidence and arguments for information sources) (Wissen Hayek et al., 2016; Cash et al., 2003).

In order to ensure user satisfaction and, therefore, high usability of a provided DSS, many technical and design issues need to be considered. Besides the actual design of the DSS, embedded information, its access and controls can be barriers to usage. To tackle these barriers and provide users with access to information, technical components (e.g., server performance and browser compatibility) and design components (e.g., the graphical user interface and layout) need to be considered to make the actual information easily accessible and applicable (e.g., Lauesen, 2005; Yao, 2010). A well-adjusted combination of these components enhances interactivity through smooth navigation and control of the provided information (Klein et al., 2012).



3. Chapter III: Planning perspective

DSSs can offer advanced information exchange, particularly interdisciplinary information, and thus strengthen transdisciplinary knowledge (Pettit et al., 2013; Zhu et al., 2013). By providing easy-to-use web-based tools, expert users (planners, public officials, institutional stakeholders, and researchers) can retrieve various pieces of information related to planning. Moreover, citizens can quickly and easily evaluate the effects of alternative public policies on future land use, and the related ES provisions (Pettit et al., 2013). Besides their supportive function in dealing with the increased complexity of the present planning tasks, DSSs can also have other multiple applications (e.g., informing, communicating, and analyzing) and can play various roles in the planning process (Lin and Geertman, 2013).

The increasing adoption of GIS for complex environmental planning and the integration of environmental issues at the beginning of spatial planning processes make it necessary to incorporate a large variety of planning and environmental data at different scales. This aspect is especially relevant for the initial stages of decision making, during strategic planning stages, and when considering the various environmental aspects, thus allowing transparency of information about environmental interrelationships (Förster et al., 2013). In order to handle and communicate this complexity, novel workflows are needed that guarantee a sound representation of ES interrelations and impacts while representing information in an understandable way. Recent research has shown that there is a lack of such supportive tools and that the implemented visualization approaches have various limitations (Zhu et al., 2013). In order to be communicable, information needs to be more scalable and flexible to accommodate new types of data (e.g., time-series). Furthermore, the implementation of alternative representation types—such as interactive and 3D visualizations which could be necessary to understand a scenario's variables from different perspectives—are still not adequately implemented in decision-support instruments (Zhu et al., 2013). Various representations of information seem to be relevant for making information comprehensible to various users or stakeholder groups and therefore support the planning process (Lieske and Hamerlinck, 2013). The demand for information in participatory settings is a driving factor for the degree of fulfillment of the decision-supportive function of the information provided in a planning process. Planning processes, such as transdisciplinary scenario development, or the exploration of alternatives, have to be supported by new, innovative and participatory DSSs (Neumann, 2010) whose success is defined by the level of accessibility of information and satisfaction of specific user group requirements (Poplin et al., 2013). Therefore, supportive information related to ES concepts requires helpful representations that make the requested information accessible and understandable to users, while offering the opportunity for these to be implemented in DSS. Interactive GIS-based 3D landscape visualizations have shown great potential as valuable communication tools in planning processes (e.g., Wissen Hayek, 2011; Pensa et al., 2013). Linking quantitative, spatially explicit indicators and realistic 3D visualizations of landscape change scenarios can facilitate the communication of trade-offs between indicator values, as well as between different demands for services provided by the landscape (Grêt-Regamey et al., 2013; Klein et al., 2013). Especially with regard to CES, realistic 3D landscape visualizations seem to be a prerequisite for assessing scenic characteristics and the aesthetic values of future land use alternatives. Visual landscape impact is measured in terms of observers' preference or judgment and ratings concerning visual aesthetic quality, which include scenic quality, visual quality, and scenic beauty (Daniel and Meitner, 2001).

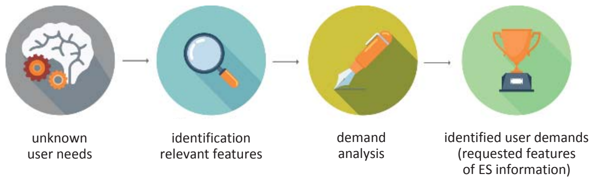
The controllability (e.g., by thematic or value filtering) of ES information and other interactive functionalities (e.g., scalability) defines the accessibility and readability of the information. DSS can offer further relevant information by using different representation types (text, graphs, tables, and so on), as well as spatial, zoomable and scalable navigation tools that are relevant to experts (Kunz et al., 2011a; Kunz et al., 2011b). The latter are also helpful for other users in various planning process stages, especially local assessment of the aesthetic and place-based values that can have a significant and individual meaning for local citizens. For such evaluations, small-scaled thematic 2D maps are not appropriate as they are still mostly used in stakeholder workshops. Scalable and navigable mapping and visualization methods are needed to better understand the spatial and contextual interaction of human relationships with the social, cultural, built, and natural environments that describe the characteristics of cultural ES, which cannot be efficiently represented by traditional cartographic methods (Carver et al., 2009).

Detailed information Paper I (Chapter IV):

Original title: Ecosystem services visualization and communication: A demand analysis approach for designing information and conceptualizing decision support systems
Authorship: Klein, T. M.; Celio, E.; Grêt-Regamey, A.
Dates: Received 14th November 2014, Revised 30th January 2015, Accepted 22th February 2015, Available online 12th March 2015
Journal: Ecosystem Services, Volume 13, June 2015, p. 173–183; Special Issue: *Best Practices for Mapping Ecosystem Services*.
URL: doi:10.1016/j.ecoser.2015.02.006

4. Chapter IV: Identification of user demands

Ecosystem services visualization and communication: A demand analysis approach for designing information and conceptualizing decision support systems



Abstract

The concept of ecosystem services (ES) is broadly established in research and in communities of interest. The European Commission (EU) has embraced these conceptual approaches in order to provide policy makers with decision-supportive information concerning the supply of and demand for ES. It is, however, not yet clear how ES information should be represented to fulfill decision-supportive functions or even to process the data in such a manner that it is understandable. Knowledge about the ideal representation and communication of ES information integrated into decision support systems (DSSs) is particularly key for guiding users through such systems. In order to determine the correct representation type for a given situation and intended use, we developed a demand analysis, distributed through an online survey, to identify user demands for ES information. A principal component analysis depicts that requirements were highly heterogeneous among respondents of this study. Five components describing the representation type can, however, be identified, depending on the situation of application and the intended use of the ES information by the respondents: (1) 3D landscape visualizations are preferred for analyzing and exploring ES-related information; (2) texts and abstracts are preferred for communication and discussion support; (3) thematic 2D map representations are preferred to support scenario development in public applications; (4) abstract 3D landscape visualizations facilitate estimations in group applications; and (5) charts and tables, in combination with thematic 2D map representations, support analyses. However, while certain representation types are function- and/or situation-specific, no representation type can be used as a panacea. A demand analysis, as presented in this paper, can contribute to the definition of how ES information is to be integrated into DSSs and how it needs to be designed to be (decision) supportive.

4.1. Introduction

The importance of providing information and improved knowledge about ecosystems and their services has been recognized by policymakers through a range of EU endeavors. The Mapping and Assessment of Ecosystems and their Services (MAES) to improve knowledge is one of the keystones of Action 5 of the EU 2020 Biodiversity Strategy (European Commission, 2011). This document defines a goal of mapping and assessing the state of ES in EU Member States by 2014 as a base to assess economic values and promote the integration of these values into accounting and reporting at the EU and national level by 2020. These data will be used to inform policy makers in many areas, such as nature, biodiversity, territorial cohesion, agriculture, forestry and fisheries, and may also inform policy development and implementation in other domains, such as transport and energy (European Commission, 2013). Additionally, the Mapping of Ecosystems and their Services in the EU and its Member States (MESEU) working group investigates the best ways to support the implementation of ES information in policy and decision-making processes (MESEU, 2014). However, the best ways in which to operationalize the ES concept and the new available data and scientific knowledge on ecosystems and ES in order to provide appropriate information to support decision making remains unclear.

Almost all approaches for mapping ES use geographic information systems (GIS), and their assessments are mostly based on thematic or remote sensing data (e.g., land use/cover as a proxy for ES supply) (Li and Fang, 2014; Maes et al., 2012; Schägner et al., 2013). The development of these approaches has become an important research topic in recent years, particularly as a result of advances in GIS technology and the availability of new data (Maes et al., 2012; Schägner et al., 2013). ES mapping approaches have the potential to support generic application at different sites, as long as input data are available. Through these GIS modeling approaches, ES information can easily be made available on a large spatial scale; however, the outcomes seem less policy-oriented to support decision making (Schägner et al., 2013). Despite the advantages of the ES concept (e.g., its strength in communicating the benefits of ecosystem conservation to diverse stakeholder groups) (Reid et al., 2006), other characteristics, such as its conceptual framework, limit the practical application of ES. Furthermore, although various methodologies and tools have been developed for quantifying, valuing, and mapping ES (Grêt-Regamey et al., 2014), there is no simple or established way of integrating the ES concept into policies and decision-making processes (Hauck et al., 2013), nor is there a standardized approach for mapping ES (Grêt-Regamey et al., 2014; Crossman et al., 2013). While available methodologies aim to produce and provide decision-supportive ES information, their developers address the challenges of technically improving the approaches (e.g., through application on different tiers) rather than of providing problem- and user-oriented ES information (Grêt-Regamey et al., 2014). Numerous studies have shown that the ES concept supports communication (e.g., Hauck et al. 2013; Orenstein and Groner, 2014). Luck et al. (2013) expanded this research stream by illustrating the various types of communication when working with ES information within user groups. They distinguished the following three aims of communication: (1) awareness raising and education, (2) strategic arguments, and (3) interdisciplinary communication. However, expert-based statements, such as "ES maps improve ES communication" (e.g., Schägner et al., 2013), as well as statements from official sources, such as "maps can be used as communication tool to initiate discussions with stakeholders, visualizing the locations where valuable ecosystem services are produced or used and explaining the relevance of ecosystem services to the public in their territory" (European Commission, 2013), are lacking in empirical foundation. This calls for a closer investigation to understand (1) which type of communication is meant, (2) whether and why maps support communication, and (3) whether alternative and more convenient representation types are available. While the applicability of ES maps has been criticized (Hauck et al., 2013), to our knowledge, no study is available that outlines strategies or discusses how to present ecosystem services information to support decision making.

Alternatives to maps, texts, charts, and tables are used to communicate ES information. Recently, new interactive features, in combination with visualizations, have been shown to enhance learning effects (Grêt-Regamey et al., 2013; Janvrin et al., 2014; Patwardhan and Murthy, 2014). Bostock et al. (2011) demonstrated that representing information as dynamic and interactive graphs or information visualizations support transparent methods of data mining. Furthermore, 3D landscape visualizations provide supportive information for group interactions in stakeholder processes, trade-off understanding, or decision-making (e.g., Grêt-Regamey and Wissen Hayek, 2013; Grêt-Regamey et al., 2013; Neuenschwander et al., 2014; Wissen Hayek and Grêt-Regamey et al., 2012), particularly in planning tasks (Wissen Hayek, 2011). Furthermore, information symbolized as 3D object features, such as a 3D statistical map in a virtual map/globe, could better support the representation of complex information data (Kraak, 1988; Tiede and Lang, 2010). In summary, these recent studies have observed that the use of a combination of different representation types, including, for example, innovative techniques for data mining, have various benefits for communication and decision making. Such an approach, therefore, should be considered as a potential alternative for providing ES information and supporting decision making.

Decision support systems (DSSs) have emerged as powerful tools especially for supporting complex spatial issues (e.g., Dagnino and Viarengo, 2014; Dagnino et al., 2013; Massei et al., 2014; Romanach et al., 2014; Yee et al., 2014). DSSs are computerized systems and, in the context of spatial decision support, are mostly linked to or based on GIS information (e.g., Jankowsky et al., 2014). Power (2001, 2008) identifies five generic types of DSSs: (1) model-driven, (2) data-driven, (3) knowledge-driven, (4) document-driven, and (5) communication-driven. DSSs with GIS-based ES information have, in most cases, model- or data-driven DSS structures (e.g., Jelokhani-Niaraki and Malczewski, 2015; Wanderer and Herle, 2014). Sugumaran and de Groote (2011) provided a further important definition for DSSs, linking Simon's (1960) explanation of psychological decision-making processes with the systematic processes of DSS. The definition of Sugumaran and de Groot (2010) is therefore important to understanding decision processes so that a DSS can be best designed to provide relevant information.

The referred theory of decision making calls for objective identifications prior to the development and evaluation of alternatives (Keeney, 1992). Decision analysis, therefore, includes optimization cycles for objective-based solution-finding. The application of a DSS does not necessarily include an optimization for finding solutions by users; however, such an option to organize, display, and manipulate information, as potentially happens in a decision-making process, could lead to a better understanding of the perceived information (Diez and McIntosh, 2011). Regardless of model type, a DSS, along with its integrated information and processes, should be tailored to the actual decision problem (Sojda et al., 2012) and developed for and with targeted end users (Lautenbach et al., 2009). The development of DSSs is often accompanied by user analyses designed to define how the information should be communicated to the heterogeneous user groups. Analogously, we have developed and carried out a demand analysis for specifying user needs to design user-friendly and relevant ES information. This demand analysis is presented in the next sections.

4.2. Methods

4.2.1. Survey

4.2.1.1. Framework definition

To identify user demands for ES information, we distinguished different types of representation based on their application and purposes. We developed a catalog of questions based on a review of questionnaires used in requirement engineering approaches (e.g., Chin et al., 1988; Davis, 1989; Lewis, 1995; Lin et al., 1997; Lund, 2001; Perlman, 1997; Prümper, 1997). Requirement engineering approaches are designed to support the development of software environments and provide user-oriented applications. The advantages of these engineering approaches are their systematic concepts, which seek to consider the full range of potential relevant aspects, identify significant features, and prioritize these features for development processes (Ko et al., 2007). We focused particularly on a demand analysis targeted at identifying user requirements of focus groups of new software products (Rupp and SOPHIST Group, 2007), as ES information is increasingly integrated into DSSs within software environments.

During the initial data collection, more than 100 factors that could be relevant for DSSs integrating ES information were identified through requirement engineering approaches (e.g. Aurum and Wohlin, 2005; Hull et al., 2011), practical application reports, and a literature review. With these factors all kind of potential relevant features and characteristics for DSS implemented ES information are described. The factors were further harmonized in relation to ES information and then categorized as described in Section 4.2.1.2.

4.2.1.2. Definition of factor categories

The choice of an initial set of factors was based on the identification of relevant factors on the characterization of the interactions among ES information communication, representation, and application. These initial factors were categorized (factor categories) into the following five areas: (1) representation type, (2) application function, (3) application setting, (4) display type, and (5) display scale (Figure 1). We understand this approach as a systematic, nested, modular approach. The factor categories can be divided into two main groups: (1) ES information (integrated in DSSs) and (2) intention to use (Figure 1). The ES information category is defined by a representation type that provides information content at a specific display scale and as a specific display type. Not all kinds of ES information can, however, be (dis-)aggregated by specific display types or display scales. The category for intention to use ES information (integrated in a DSS) is defined by the specific situation and the specific way in which users expect to be supported. The link between the factor categories and the decision-making process (Sugumaran and de Groote, 2011) presented in Figure 1 shows that information communication, representation, and application are embedded in different steps of the decision-making process.

4.2.1.3. Definition of factors

The factor categories (Figure 1) that were ultimately considered in this study's analysis are shown in Table 1. In the following, the factors are briefly described.

Representation types:

Representation types of ES information comprise relevant visual techniques for displaying information: *Photorealistic 3D landscape visualizations* and *realistic 3D landscape visualizations* use 3D object libraries that can be linked to GIS data to reproduce landscapes in a realistic way (e.g. Grêt-Regamey et al., 2013; Wissen Hayek, 2011). In contrast, *abstract 3D landscape visualizations* focus on providing key information relevant for decision makers (Wissen Hayek, 2011). *Thematic 2D map representations* describe standard cartographic maps (including web-based maps) for given topics (e.g., Iosifescu-Enescu et al., 2010; Venezky, 1972). *Statistical 3D map representations* describe an amalgamation of *abstract 3D landscape visualizations* and *thematic 2D map representations*. They use cartographical elements, such as legends, integrated into three-dimensional symbolizations (e.g., a 3D extrusion of land boundaries by specific attribute values), which can be accessed, for example, through virtual globes (e.g., Lie et al., 2015; Kraak, 1988; Tiede and Lang, 2010). *Graphs/information visualizations* comprise interactive data mining and explorative visualizations. Also known as data-driven documents (D3), visualizations of this representation type exhibit high communication transparency by allowing access to unfiltered data sets (Bostock et al. 2011) and the representation of complex information, which is directly and interactively navigable or filterable within the visualized information (Janvrin et al., 2014). With *texts and abstracts*, *charts*, and *tables*, we refer to standard representation types with normal characteristics; these require no further description.

Display scales:

Depending on user interests and applications, the identification of relevant scales plays an important role in the provided ES information (e.g., Grêt-Regamey et al., 2014). We differentiate here among *global*, *continental*, *EU-wide*, *national*, *sub-national*, and *local scales*. In the demand analysis, all scales were introduced by a schematic illustration, in which the EU-wide and national scales were defined by political boundaries.

Display type:

The way in which data are aggregated or disaggregated is crucial for the accessibility, readability, and applicability of ES information (e.g., Abram et al., 2013; Bagstad et al., 2013; Li and Fang, 2014). For this, we explicitly addressed such factors as *spatial-*, *temporal-*, and *content*-based *explicitness* and the *aggregated*, *selectable/filterable* styles and characteristics of the information.

Setting of application:

The contexts in which ES information is used require different representation and display types. Studies have shown that these representation and display types feature various properties and, hence, are not equally attractive to users (Wissen Hayek, 2011). For our analysis, we defined the context of *personal application* to be a situation in which ES information is used without the involvement of any further persons. *Application in a group* describes ES information application in a smaller group (e.g., a few colleagues). The context *public application* applies to situation involving numerous people (e.g., a presentation or workshop situation).

Functions in application:

The definitions of the possible basic functions of ES information in DSSs are based on Brömmelstroet (2013) and consist of informing (*information of content*), communicating (*communication of content*), and analyzing (*analysis of content*). The factor information of content describes the function of a user transferring ES information, without any further intentions. In contrast, communication of content describes the aim to facilitate the communication and flow of ES-related information among users. The factor analysis of content is defined by the processing of data or information in order to find patterns and underlying processes for evaluation (Brömmelstroet, 2013).

In addition to these basic functions of ES information integrated in DSSs, we found it important to define further functions in order to differentiate among the detailed properties of various demands. Through these additional supportive functions of ES information provision, it becomes possible to link group interacting processes (e.g., Brömmelstroet, 2013), roles of stakeholder engagement (e.g., Cairns et al., 2013; Maguire et al., 2012; Pomeroy and Douvere, 2008), and relevant stages of individual decision analyses of decision-making processes (Keller, 1997; Simon, 1960; Sugumaran and de Groote, 2011) (Figure 1). We additionally included the factors *exploration of content* (to describe the inspection of provided ES information, without any deeper analysis), *support of decisions* (to detect ES information or DSS features directly applicable to decision making), *support of discussions* (to identify relevant factors that support group interactions based on discussion), *support of voting* (to determine supportive factors for group interactions based on voting), *support of scenario developments* (to uncover factors that may benefit developing scenarios), *support of estimation* (to determine relevant factors that assist with estimations concerning providing ES information without further analysis), and *support of assessments* (to assess retrieved ES-related issues).

4.2.1.4. Survey design

The survey asked participants for feedback on the importance of the potential/meaning (ranking or scoring) of a factor in context to the respondent's occupational activity or projects, as well as on which factor was most important or relevant to the respondent, given ratings of factor categories. Participants could also add their own suggestions.

The final survey consisted of 34 questions, including 59 factors, categorized as depicted in Table 1. The factors and their characteristics were introduced and explained in the survey. For this explanation, we referred to a literature review of the concepts of data and information visualization, communication approaches of spatial information, cartography methods, decision-making processes, and designs of DSSs (e.g. Simon, 1960; Sugumaran and de Groote, 2011; Terry, 2014; Tyner, 2010; see Appendix I). Furthermore, to improve participants' understanding of the questionnaire, we conducted a pre-test with ten participants to make further refinements to the questionnaire structure, factor descriptions, and questions.

Several questions queried more than one factor at the same time by connecting two factors from different categories (e.g., "Which representation type should be used for which situation?"). Most factors were queried in various contexts and for different categories to identify correlations. Table 1 shows the generalized survey questions for the factors. These questions were further rephrased (e.g. as task) depending on used answer type. Additional questions included factors concerning temporal application, the availability of functionalities, use as decision support tools, and demographic aspects (e.g., focus, age, occupational function). The questions were introduced by short texts; categories and factors were described and illustrated by pictures. To avoid ambiguous factor definitions, we provided additional background information for each picture (see Appendix I). Respondents were assured of the anonymous nature of the survey and asked to complete the questionnaire fully. They were told that the survey would take approximately 15 to 35 minutes (depending on knowledge and experience of factor categories) to complete. Most of the questions were measured on a five-point Likert scale (*no benefit to high benefit; not given to strongly given*). However, dichotomous and ranking questions were also designed to collect detailed feedback on the significance of the factors. Furthermore, open questions allowed respondents to provide special requirements. Table 1 indicates which answer types were used in the survey (i.e., filtering, open, ranking, and scoring). The full questionnaire is provided in Appendix I.

4.2.1.5. Survey dissemination

The survey was disseminated via the web. The survey URL was published in December 2013 on various social media platforms for users who would potentially be interested in ES, such as LinkedIn (e.g., Ecosystem Services: Mapping, Visualization and Communication group), Facebook, Twitter, and Research Gate. It was also posted on relevant websites and news blogs by various other communities (e.g., www.es-partnership.org) and projects (e.g., www.operas-project.eu). Within three months, the survey link was fetched approximately 1,600 times. About 450 surveys were filled by the end of March 2014. To identify potential relations among all the categories and factors, only fully completed questionnaires could be used (n=117).

4.2.2. Principle component analysis

To analyze the significance of various factors and their relations with one another, we used a principal component analysis (PCA). PCA is a widespread statistical technique (e.g., Masto et al., 2008; Qi et al., 2009; Yu et al., 1998; Zhu et al., 2008) that facilitates the identification of a set of new variables or indicators (denominated principal components, or PCs) from an initial, broad set of variables or factors. These new variables are independent, which means that the variance of the studied resource or system explained by one of the variables is, ideally, not explained by any other variable of the new set. Therefore, this technique facilitates the identification of the underlying dimensionality of the initially considered variables.

Because the respondents provided multiple answers for each factor, a recoding was undertaken using the filter questions to weight the values of the scoring and rating questions. The recoded rating and scoring values of each factor provided the base for the PCA. Based on statistical validation, some factors were excluded from further analysis. The original set of factors (Table 1) was checked for acceptability using Bartlett's sphericity test ($P < .001$) and the Kaiser-Meyer-Olkin criterion ($KMO > 0.632$), both of which showed satisfactory

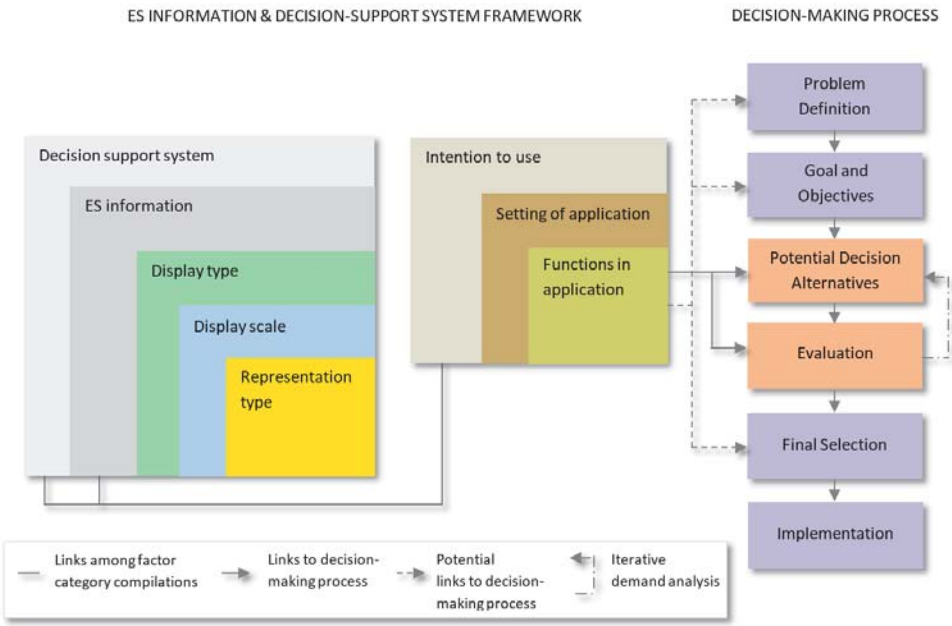


Figure 1 - Framework of factor categories and their relations in the context of ES information integrated into the DSS and decision-making process theory adapted from Sugumaran and de Groote (2011)

values for running a PCA, following the exclusion of factors. Table 3 shows the reduced set of 25 factors that were further considered for the PCA. The internal consistencies of the resulting components were further checked using Cronbach's alpha, resulting in five consistent components. All of the coding and statistical analyses were conducted using IBM SPSS Statistics 23 (IBM, 2013).

4.3. Results

4.3.1. Principal components

Of the 450 questionnaires obtained, only 117 were fully completed and usable for the PCA. The PCA resulted in 25 components, which had to be further reduced by applying the eigenvalue criteria to obtain interpretable results. In order to define a minimum factor set from the five categories, the first nine principal components (PCs) with eigenvalues greater than one (i.e. KMO) were considered for further analysis. These nine components accounted for 63.14% of the total proportion of the explained variance (Table 2).

Tests for internal consistency showed that two components (PCs 4 and 6: Cronbach's alpha > 0.5 and < 0.6) had a tolerable consistency and that three components had an acceptable consistency (PCs 1, 2 and 5: Cronbach's alpha > 0.6).

Table 1 - Eigenvalues obtained after the application of the PCA to the reduced set of factors.Loadings of less than 0.3 were suppressed to indicate the relations more clearly.

Principal Component	Eigenvalue	Proportion (Variance)	Cumulative Variance
1	**3.757**	**15.030**	**15.030**
2	**2.102**	**8.410**	**23.440**
3	**1.928**	**7.712**	**31.151**
4	**1.671**	**6.685**	**37.836**
5	**1.465**	**5.862**	**43.698**
6	**1.335**	**5.341**	**49.039**
7	**1.267**	**5.068**	**54.107**
8	**1.143**	**4.572**	**58.679**
9	**1.115**	**4.461**	**63.140**
10	.911	3.643	66.783
11	.882	3.528	70.311
12	.813	3.250	73.562
13	.794	3.175	76.736
14	.701	2.802	79.538
15	.669	2.676	82.215
16	.625	2.499	84.714
17	.594	2.374	87.088
18	.534	2.137	89.226
19	.504	2.017	91.243
20	.462	1.847	93.090
21	.429	1.715	94.805
22	.393	1.573	96.378
23	.379	1.518	97.896
24	.293	1.172	99.068
25	.233	.932	100.00

Thus, the inferences from this study regarding the statistical validation parameters are based on these five PCs. We suppressed all loadings of factors (eigenvectors) below 0.3, as this is the most common standard value for discovering PCA results (e.g., Child, 2006). Furthermore, the variation between the factors with loadings lower than 0.3 and the multiple high-loading factors (>0.6) of each PC indicates that there are more significant relationships among high-loading factors than among lower-loading factors. Thus, we discounted loading factors of less than 0.3 (Table 3).

The first PC (PC 1, Table 3) had high positive loadings for the factors related to 3D landscape visualizations as representation types of ES information (*photorealistic 3D landscape visualizations*, .698; *realistic 3D landscape visualizations*, .675; *abstract 3D landscape visualizations*, .488; *statistical 3D map representations*, .564). Furthermore, factors associated with analytic *functions in the application* of ES information also obtained high loadings on PC 1 (*exploration*, .623; *analysis of content*, .472).

It is not surprising that the factors describing the 3D landscape visualization types are grouped with factors associated with analytic and explorative functions, as it is known that 3D visualizations can fulfill various functions and support individual processing, participant discussions, and the achievement of the objectives of information transfer (Wissen Hayek, 2011). Thus, 3D landscape visualizations seem to support, in particular, functions of exploring and analyzing ES information. This finding was also observed by Stock et al. (2007). According to the conceptual learning styles and processes described by Kolb (1984), an experimental and explorative use of information (Kolb and Kolb, 2005), as depicted by the factor loading of *exploration of content* on PC 1, supports an analytic function. This relationship between both *functions in application* (i.e., *exploration of content* and *analysis of content*) seems to help users find patterns and underlying processes of provided information, as emphasized by Brömmelstroet (2013). This combination of functions could more comprehensively strengthen the understanding of ES information in the broader environmental context through a recognition of the underlying correlations and dependencies of ES.

The high loadings of the second PC (PC 2, Table 3) obtained for the representation type *text and abstracts* (.629), together with functions of *communication of content* (.734) and *support of discussions* (.628) indicate that written facts seem to be a widely demanded format for the communication of ES content in general. Other positive loadings on this component occurred mostly for factors associated with the category of *representation types* and *functions in application*, but further related to the *setting of application*.

The high loading of *support of discussions* as *function in application* on PC 2 implies that *texts and abstracts* can further support dialogs among stakeholders, as proposed by Nelson et al. (2002), or transfer knowledge and experience between research and practice (de Groot et al., 2010).

The third PC (PC 4, Table 3) had high positive loadings for the factor *public application* (.704) from the category *setting of application*. Moreover, the factors *scenario development* (.771) and, to a lesser degree, *support of assessments* (.321) as *functions in application* received high loadings.

The grouping of these factors on PC 4 seems logical, considering that participatory processes and stakeholder involvement in strategic planning are important for collecting viewpoints from different disciplines and for the construction and communication of ideas regarding landscape alternatives (Šantrůčková et al., 2013).

Furthermore, the representation type of ES information that received a moderately high loading on PC 4 was *thematic 2D maps* (.391), which underlines the importance of *thematic 2D maps* in participative processes. In spatial planning, apparently, *thematic 2D maps* facilitate assessments (*support of assessments*), as described by Grêt-Regamey and Wissen (2013). This process is strongly integrated into scenario development approaches in participative planning. Allowing access to basic information through, for instance, indicator or criteria maps for landscape scenarios or alternatives, as proposed by Grêt-Regamey and Wissen Hayek (2013), may facilitate planning processes and allow involved stakeholders to assess the credibility or scenario sustainability with the explicit spatial information depicted in the maps (Wissen Hayek, 2012).

On the fourth PC (PC 5, Table 3) high positive loadings were obtained for factors from the categories *setting of application* (*group application*, .598) and *abstract 3D representation types* (*abstract 3D landscape visualizations*, .625*; statistical 3D map representation*, .311). The grouping of these factors in PC 5 further underlines the benefits of *abstract 3D visualizations* in participative processes or in application settings in groups, as described by Wissen Hayek (2011) and Buckley (2000). Such abstract visualizations support the illustration of invisible or abstract phenomena in 3D landscape environments, as described by Buckley (2000).

Furthermore, abstract visualizations can provide information on the correlations among multiple factors, thus allowing for rough analyses and evaluations (Wissen Hayek, 2011). The latter could be also explained by the highly loaded factor of function in application of *support of estimations* (.754) in this PC. Wissen Hayek (2011) also concluded that these abstract 3D visualizations were suitable for *group application*.

Finally, high positive loadings on the fifth PC (PC 6, Table 3) were mainly associated with the category of *representation types* (*thematic 2D map representations*, .494; *charts*, .791; and *tables*, .608). This indicates that there is a demand for an advanced, coherent display type of map representations. Furthermore, *analyzing of content* (.394) received a moderately high loading on PC 6, which implies a need to combine spatially explicit information (e.g., *thematic 2D map representations*) with more detailed information (e.g., *charts or tables*) for the *analysis of content*. Regarding the function of application, Tyner (2010) emphasizes the importance of cartographic design and relevant map content in achieving the provision of specific information. For maps provided via non-print media (e.g., web-based maps or maps integrated with DSS), this means that there is a demand for functionalities requiring additional information in the map content. Such user-specific needs could be implemented through interactive map designs: For example, users could have access to integrated analytic map tools or personalized map layout features to allow, for example, the reclassifying or re-coloring of ES information, according to their specific interests.

4.3.2. Respondents' characteristics

To enable a description of the respondents, a comparison of the full data set and the sample that fully completed the questionnaire (n=117) was undertaken. This comparison facilitated a better interpretation of the PCA results. The sample size varies between the data sets, since it depends on the last question completed by the respondents (Figure 2, Figure 3).

Figure 2 shows the respondents' fields of occupation (each respondent was allowed to choose a maximum of three fields) for the full set (n=450) and for the sample used for the PCA (n=117). Feedback was received mainly from the research sector, followed by the private industry sector, the "others" (i.e., policy, non-profit, education) sector, and the administration sector (Figure 3).

Table 2 - Implemented survey questions on factor categories for the full set of factors with answer options considered in the PCA. The spread and the full questionnaire are available in the Appendix I.

Factor category	Factor (answer options)	Description	Answer Type S	O	F	R	Generalized question (These questions were adapted according to used answer type)
Representation type of ES information	Photorealistic 3D landscape visualizations	The visual quality of the representation is similar to that of a real photograph	x	x	x		• How do you assess these types of representation as potential information carriers for the content of your professional project activity? Please also consider the relationships among the assessed potentials. • What types of representation would you personally prefer for your professional activities/projects?
	Realistic 3D landscape visualizations	For example, all content displayed as realistically as possible	x	x	x		
	Abstract 3D landscape visualizations	For example, buildings colored by their heights	x	x	x		
	Statistical 3D map representations	For example, building heights related to building values	x	x	x		
	Thematic 2D map representations	Combinable maps edited by topic	x	x	x		
	Graphs/information visualizations	For example, the representation of dependencies	x	x	x		
	Texts and abstracts	Texts and abstracts	x	x	x		
	Charts	For example, pie, bar, and line charts	x	x	x		
	Tables	Various content and related values listed in tables	x	x	x		
Function in the application of ES information	Information of content	Provision of content-related information		x	x	x	• Which of these aspects in your occupation or projects could be supported by a DSS? In your assessment, please also consider the relationships among the different aspects. • Which of these functions would be most important for you, personally, in the application of a DSS?
	Exploration of content	Exploration of content		x	x	x	
	Analysis of content	Evaluation of content		x	x	x	
	Communication of content	Support of communication of content		x	x	x	
	Support of discussions	Support of discussions	x	x	x		
	Support of scenario developments	Support of scenario developments	x	x	x		
	Support of estimation	Support of estimation	x	x	x		
	Support of assessments	Support of assessments	x	x	x		
	Support of voting	Support of voting	x	x	x		
	Support of decisions	Support of decisions	x	x	x		
Setting of application	Public application	For example, during a workshop or a presentation	x	x	x		• How would you evaluate the application potential of this platform, depending on the situation? • Which of these DSS application settings would be most relevant for you?
	Application in a group	For example, in a group of colleagues	x	x	x		
	Personal application	Independent application	x	x	x		
Display type	Spatially explicit	Quality ratings are exactly spatially located		x	x	x	• Which display type is, in your opinion, the most meaningful for the content of your projects or occupation? • Which of these types of representation are most important for you?
	Spatially aggregated	Different spatially located qualities are aggregated		x	x	x	
	Temporally explicit	Quality ratings are temporally corresponded (e.g., to a scenario)		x	x	x	
	Temporally aggregated	Quality ratings are aggregated by period (e.g., of time courses)		x	x	x	
	Spatially selectable/filterable	Quality ratings can selected/filtered by location		x	x	x	
	Temporally selectable/filterable	Quality ratings can be selected/filtered for specific periods/stages		x	x	x	
	Composite content	Quality ratings of an indicator are displayed (e.g., without underlying or influencing factors)		x	x	x	
	Itemized content	Quality ratings of an indicator are displayed (e.g., by values of underlying and influencing factors)		x	x	x	
	Selectable/filterable content	Quality ratings can be selected/filtered (e.g., by constraints)		x	x	x	
Display scale	Global scale	For example, world map		x	x		• In which scales do you most often operate within your professional activities or projects? • On which scale is information presented in your professional activity and your projects? • Which scale(s) would you personally prefer with regard to the readability of the content of your professional activities and projects?
	Continental scale	For example, European map		x	x		
	EU-wide scale	Political borders of EU		x	x		
	National scale	National map		x	x		
	Sub-national scale	Sub-national map		x	x		
	Local scale	Local map		x	x		

Available answer types in questionnaire: F = Filtering, O = Open, R = Ranking, S = Scoring; ■ = Representation type; ■ = Function in application (support function); ■ = Setting of application; ■ = Display type; ■ = Display scale

Table 3 - Loadings of eigenvectors following the rotation obtained through the PCA. Loadings of less than 0.3 were suppressed to indicate the relations more clearly.

Category	Factor	Principal Components (PC) 3D landscapes 1 α = .692	Communication 2 α = .616	3* α = .038	Public application 4 α = .561	Group application 5 α = .633	Analytic maps 6 α = .511	7* α = .446	8* α = .234	9* α = .052
Representation type of ES information	Photorealistic 3D landscape visualizations	.698								
Representation type of ES information	Realistic 3D landscape visualizations	.675								
Function in application of ES information	Exploration of content	.623								
Representation type of ES information	Statistical 3D map representations	.564	.303			.331				
Function in application of ES information	Analysis of content	.472					.394			.304
Function in application of ES information	Communication of content		.734							
Representation type of ES information	Texts and abstracts		.629							
Function in application of ES information	Support of discussions		.628							
Display scale of ES information	Continental scale			.694						
Display scale of ES information	Local scale			-.653						
Display scale of ES information	Global scale			.607						.322
Function in application of ES information	Support of scenario development				.771					
Setting of application	Public application		.327		.704					
Function in application of ES information	Support of estimations					.754				
Representation type of ES information	Abstract 3D landscape visualizations	.488				.625				
Setting of application	Application in a group					.598		-.323		
Representation type of ES information	Charts						.791			
Representation type of ES information	Tables						.608	.335		
Representation type of ES information	Thematic 2D map representations				.391		.494		.391	
Function in application of ES information	Support of assessments				.321			.774		
Function in application of ES information	Support of voting							.530		
Display type of ES information	Temporally aggregated								.736	
Function in application of ES information	Information of content			.406					.458	
Display scale of ES information	EU scale			.343						-.740
Display type of ES information	Selectable/filterable by content		.345							.591

* These principal components (3, 7, 8, 9) will be ignored due to poor internal consistency.

α = Cronbach's alpha

■ = Representation type; ■ = Function in application (support function); ■ = Setting of application; ■ = Display type; ■ = Display scale

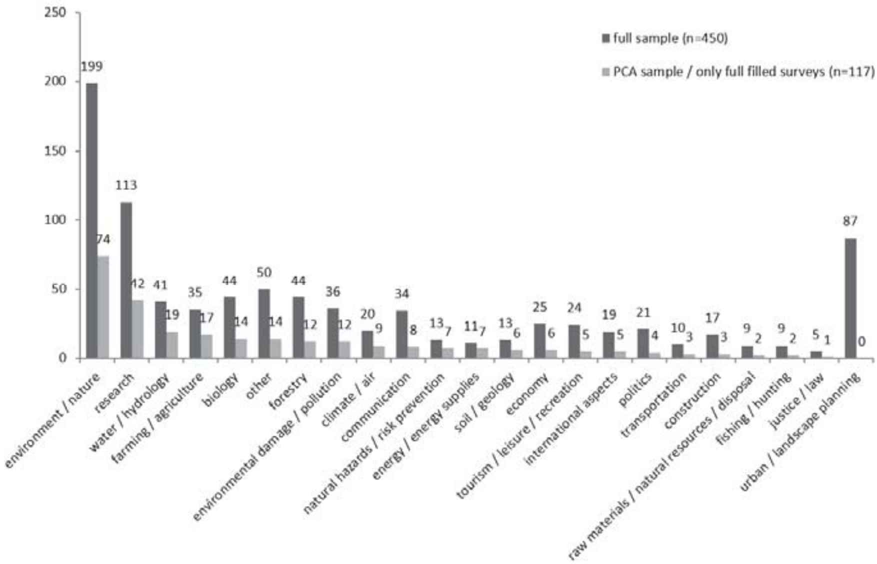


Figure 2 - Occupations of respondents. The diagram shows respondent occupations for the full sample and for the PCA

If we expand our scope and process to all received responses, the resulting components *public application* (PC 4) and *analytic maps* (PC 6) contain, additionally, the factor *thematic 2D maps* as a representation type representing map applications. In sum, 23% (n=252) of respondents preferred maps for their tasks. When compared to the demand of other representation types, the significance of these two components can be confirmed*: thematic 2D maps* are requested as a representation type of ES information to support applications in public situations (*application in public*) and for analytic functions (*analysis of content*). However, while we see this pattern when taking into account all results, the lack of this result in the PCA suggests that it might be a common understanding that maps are important for communication, but that only specifications of mapping information make their use effective. Requests, such as the ones from the EU Biodiversity Strategy to map ES by 2014 (European Commission, 2013), might not be specific enough to support decision making. This interpretation of the results is also supported by the following: While the EU strategy necessitates representing ES information in a pan-European scale by using global ES classifications to provide comparable information across different parts of Europe's territory (European Commission, 2013), this approach was not demanded by the respondents of

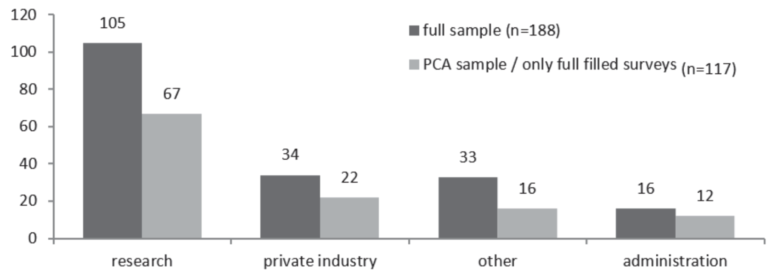


Figure 3 - Respondents' fields of employment. Diagram shows the full sample and the PCA sample (only fully filled surveys).

our survey results: Only 5% of the respondents (n=222) required an EU-wide scale for displaying ES information. The majority were more interested in a more detailed display scale (sub-national scale, 36%; local scale, 33%) than in coarser ones (national scale, 12%; European scale, 5%; continental scale, 4%; global scale, 6%). This is also supported by the demand for 3D landscape visualizations (PC 1): These representation types are characterized by a higher level of detail at a closer view than those at a smaller scale, and they were preferred over non-abstract representation.

Finally, when analyzing the full dataset, we see that most respondents would have welcomed the opportunity to access decision-supportive ES information (69%, "would like;" 19%, "possibly;" 3%, "under certain conditions;" 2%, "denied a use;" n=122) and saw a benefit in using DSS with integrated ES information for their specific tasks (26%, "high benefit;" 37%, "benefit;" 15%, "neutral;" 1%, "rather without;" 2%, "no benefit;" n=153). Such a pattern is not seen in the PCA. Again, we see that we have a large heterogeneity in the specifications: 39% would use DSS for *analysis of content*, 22% for receiving *information of content*, 20% for *communication of content*, and 12% for *exploration of content* (n=281). This strong variability across DSS applications, along with the intention of ES information application, again emphasizes the importance of providing appropriate *representation types* tailored to specific user demands.

4.4. Discussion

4.4.1. Demand analysis approach

Our study determines the most important representation types needed to communicate and visualize ES. These include: (1) 3D landscape visualizations, which are preferred for analyzing and exploring ecosystem services information; (2) texts and abstracts, which are preferred for the communication and support of discussions; (3) thematic 2D map representations, which are preferred to support scenario development in public applications; (4) abstract 3D landscape visualizations, which facilitate estimations in group applications; and (5) charts and tables, in combination with thematic 2D map representations, which support analyses.

However, the study also clearly shows how heterogeneous the demands are, and that, as in DSS application (Pettit et al., 2011), it is important to conduct a demand analysis to customize solutions to specific cases. The resulting principle components of our demand analysis indicate that users prefer specific representation types for ES information. These types depend on the possible use of the information (*function in application*) and the situation in which the users want to apply the information (*setting of application*; Table 1). These outcomes refer to specific user demands consisting of various categorical features, reflecting findings in practical applications from other studies (e.g., Karjalainen and Tyrväinen, 2002; Terry, 2014; Tyner, 2010; Wissen Hayek, 2011). For example, 3D landscape visualizations in landscape planning may facilitate the communication of visions and support learning processes (Grêt-Regamey and Wissen Hayek, 2013; Grêt-Regamey et al., 2013; Lange and Hehl-Lange, 2010; Wissen Hayek, 2011; Wissen Hayek et al., 2012a). Hence, landscape visualizations are powerful tools to support decision making in planning processes (Bryan, 2003). Other studies (e.g., Neuenschwander et al., 2014) have made similar observations: that an integration of 3D visualization workflows in planning processes facilitates the development of alternatives for urban landscapes, while making stakeholders aware of the explicit ES trade-offs that have to be made. Additionally, a combination of 3D landscape visualizations, together with ES maps, were shown to support communication between scientists and stakeholder groups (Neuenschwander et al., 2014). However, various visualization techniques and formats of representing spatial information could cause several affective behaviors, which should be taken into account. For example, 3D landscape visualizations have limitations with regard to addressing transparency in information; for this reason, they could have lower credibility (Downes and Lange, 2014). Realistic 3D landscape visualizations can otherwise affect the specific feelings and emotions of users (e.g., users' sense of place), which are not included in other representation types (Downes and Lange, 2014). Therefore, information should be customized according to its appropriateness in order to control perceptions (e.g., van Lammeren et al., 2010; Appleton and Lovett, 2003).

To determine which representation type of ES information supports which specific applications, situations, and user groups, we categorized the questionnaire by these aspects and surveyed for support functions that described the participants' intention to use provided information (e.g., *support of voting, support of discussions*; Table 1). These functions of support were also included in the PCA and created a link to individual decision-analysis processes through optimization cycles, choices, or solution-finding (Simon, 1960; Sugumaran and De Groote, 2011). All resulting PCs contained at least one factor from the categories *functions in application* and *representation type*. Hence, demands for ES information are not strictly linked to a single representation type; instead, this circumstance requires a consideration of the other linked factors that are related to these potentially applicable media. Therefore, as our resulting PCs show, there is a need to provide different representation types to support specific demands, depending on users' intended uses and on the situation of application, according to a heterogeneous group of ES information users.

These findings also correlate with the results of Hauck et al. (2013) regarding benefits and challenges of ES maps at different levels of decision making. The resolution and level of detail of ES maps are largely insufficient to support decision making at a local scale. As de Groot et al. (2010, p.267) remarked: "traditional 2D maps are not suitable for representing multiple services at a single location or the spatial and temporal services supply changes. Dynamic visualization alternatives need to be explored to allow for representing changing bundles of services in space and time." In this context, *graphs/information visualizations*, which were included as factor in the survey, could have great potential (Bostock et al., 2011). For example, free libraries of D3 visualizations are available (www.d3js.org). These libraries allow an exploration of complex ES information through the data mining approach (with a few libraries of spatial information also available). Especially for complex and large data sets, which could occur in data-driven DSS, an implementation of these libraries could be meaningful to raise the transparency and credibility of ES information (Janvrin et al., 2014). Moreover, some ES are difficult to map and render visible—an issue that is especially relevant for the explorative and analytic uses of information (Martínez-Harms and Balvanera, 2012).

However, our study was contradictory, in some areas, to the studies of Hauck et al. (2013). Based on their findings, Hauck et al. (2013) particularly suggest using maps as a communication tool. This statement agrees with the statements of the EU Biodiversity Strategy (European Commission, 2013); however, it differs from our PCA results concerning the intention of using maps (PCs 4 and 6) and the preferred representation types for communication (PC 2), as well as the findings of de Groot et al. (2010) regarding the weakness of maps. The only analogy to our study is the intention of using maps in the context of information provision (PC 4). Other studies, such as that by de Groot et al. (2010), have further concluded that using maps in combination with GIS models to analyze and visualize impacts of ES management is beneficial. This recommendation of using maps as tools for analytic functions is particularly consistent with our results (PC 6). However, according to our results concerning the representation of information, other types of communication, such as all kinds of 3D visualizations (PC 1), seem more appropriate to support these analytic tasks. In general, the principle components of our study suggest a reassessment of the general use of *thematic 2D maps* for ES information, especially with respect to its implied support functions (*function in application*), the various formats (*representation type*), and the additional technical limitations of common methods concerning useful representation (e.g., most cultural ES cannot be verified or even rendered through maps). However, when combined with more detailed information in charts and tables (PCs 4 and 6), ES maps seem to be an appropriate format for public application with a supportive function in scenario development and analytic use.

Interestingly, it seems that respondents cannot interpret decision support in the context of applying ES information, as no PC (Table 3) included decision support (*support of decision*, see Table 1) as a directly intended use (*function in application*). This feedback behavior could refer to the quality of the decision-making process, which is characterized by individually distinct cycles of demand analysis and solution optimization (Keller, 1997; Simon, 1960). This process encompasses various stages represented by other support functions, each of which requires a different processing of ES information. The kind of ES information or function required for each of the different stages depends on individual preferences, skills, and characteristics. This procedure of processing and examining information for the solution-finding and optimization of decision alternatives describes the individual and stepwise process of decision making, as it is also explained by the different phases of spatial decision making (e.g., Simon, 1960; Keller, 1997). These potential cycles in the systematic decision-making process refer to the sharing and application of ES information. Depending on individual demands for decision analysis, ES information can be used differently (*support functions*). This decoding of ES information and its applications using our approach creates a convenient link between user-demanded factors and the systematic approach of a DSS (Sugumaran and de Groote, 2011).

4.4.2. Shortcomings and challenges

In the present study, the five components of the PCA show considerable differences with regard to the demands of the respondents of the online ES community (n=117), particularly in, for example, the application and format of ES information. This heterogeneity in user demands also leads to a variance of factor settings in the PCA. The preferences of users for factors (Table 3) could also depend on other characteristics, such as expertise or demographics. However, to uncover such personal characteristics using a PCA, a larger sample size would be necessary. Alternatively, in the case of a small sample size, these characteristics should be combined to allow their importance or relevance to still be extracted, despite the lower number of factors.

Although the questionnaire asks for personal preferences, it is not clear how the relatively large group of respondents working in research influenced the results. Their research focus potentially reflects project demands or development goals instead of personal and practical needs. While their specific research field remains open, a common interest in ES information can be assumed.

Unfortunately, large sample sizes are usually unrealistic for studies focusing on project or case specific user groups. Further, combining factors to obtain significant PCA results goes against the basic idea of such a survey because a demand analysis aims to consider all relevant user needs in detail. For that reason, an iterative demand analysis using a questionnaire could be more helpful. Here, in a first step, general demands could be queried. In a second step, only the most relevant demands from the first survey could be queried in more detail. Such a stepwise analysis could also result in a higher return rate of the questionnaire, since the questionnaire could be shortened (thus reducing the chances of negative feedback concerning survey length, which we received in the present study).

Although some factors had to be excluded due to the statistical validation process, resulting in only five PC results, these results describe 41.327% of the total proportion of the explained variance (Table 2). This low variance again indicates the strong heterogeneity of the respondents' demands for ES information integrated with DSS. For the resulting PC 3, which is not further explained or discussed due to its low validation parameters (α = .038; Table 3), a total proportion of 49.039% (Table 2) was reached. All resulting nine PCs would describe a total variance of 63.140% (Table 2). The loading factors of the excluded PCs, by statistical validation, could allow for further explanations; however, it is unclear whether their combinations would be the same if the response rate were higher. Furthermore, some of the loading factors of PC could be interpreted as logical conclusion, thus seeming relatively unhelpful. For example, respondents who are interested in a more local scale do not prefer a continental or global scale (see PC 3; Table 3). Such information seems to be less interesting for DSS development because it describes the logic of factor priorities.

There is a further lack of clarity regarding how excluded factors need to be further considered, since they were rejected for further consideration in the PCA due their poor statistical validation results. A solution could be a step-wise analysis (as described before) by, for example, factor categories, which would facilitate querying even more details on single factors and avoiding result biases due to the setting of large factors all at once.

4.4.3. Applicability in the case of the EU Biodiversity Strategy to 2020

Irrespective of the plan for developing a DSS, a demand analysis allows an identification of user demands for ES information. This approach could be helpful, therefore, for development of a communication framework for considering the heterogeneity of recipients. The EU Biodiversity Strategy to 2020 (EU, 2011) aims to promote the "active involvement of stakeholders, key policy sectors and civil society" and describes this involvement as "fundamental to the success of the new 2020 Biodiversity Strategy." Initially uncovering the demands of the heterogeneous society could contribute to a more efficient consultation through tailored ES information. As a result, users might feel more involved because they may be able to better read, understand, and apply the provided ES information, while participating or participating in decision making within the strategy adaption process (rather than simply engaging through due consultation and invitations to processes).

Given this knowledge about the user demands of different sectors and the parts of society that should be involved, an adaption process of the EU Biodiversity Strategy could be aligned to the heterogeneous biases and various interests and skills of participants. Furthermore, this would actually lead to a more transparent process, facilitating the realization of a better consideration of stakeholder interests. Although the strategy does not give concrete information regarding how the "mapped and assessed states of ecosystems and their services" will be communicated, or even detail plans on the adaption's "look," it would be difficult for public awareness and widespread society support of the strategy to be achievable when ES information is not sufficiently provided for different needs (e.g., school education purposes).

4.5. Conclusions

This paper investigated a potential workflow for identifying the demands for ES information. However, we emphasize that the presented PCA results do not necessarily support general statements about demands on ES information. Instead, with the developed demand approach, DSS concepts can be specified in more detail, the most relevant ES information to be integrated into DSS can be identified, and the ways in which such information needs to be designed to be supportive can be determined. The results of the survey of potentially interested users of ES information indicate that specific representation types are required, depending on the support function needed and the situation in which the information is to be applied.

The results show that these specific characteristics are very heterogeneous (i.e., respondents prefer 3D visualizations for explorative and analytic uses; texts for general communication; maps for public applications with a specific supportive function, such as scenario development; abstract visualizations for group applications; and maps combined with further detailed information, such as charts and tables, for analytical uses). These components present a wide variety of demands. Indeed, our sample of respondents represents a broad profile within the ES community, with no case-specific group of potential users of DSSs or specific ES-related topic. Nevertheless, we can state that an application of a demand analysis facilitates the uncovering of the complexity of the need for ES information.

We conclude that making general recommendations on how ES information should be represented and communicated is difficult: The framework of ES information demands depends heavily on the contexts in which the information is intended to be used and on its specific function. In particular, unknown interests make it nearly impossible to prepare applicable and satisfactory ES information. A demand analysis, such as we present here, is a first step toward preparing and providing case-specific, relevant, practical, and supportive ES information. In particular, we discovered that certain representation types are function- and/or situation-specific and that no representation type could be used as a panacea.

Acknowledgments

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Detailed information Paper II (Chapter V):

Original title: Shedding light on the usability of ecosystem services – based decision support systems: An eye-tracking study linked to the cognitive probing approach
Authorship: Klein, T. M.; Drobnik, T.; Grêt-Regamey, A.
Dates: Received 6th November 2015, Revised 24th March 2016, Accepted 7th April 2016, Available online 12th May 2016
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5. Chapter V: Usability testing

Shedding light on the usability of ecosystem services – based decision support systems: An eye-tracking study linked to the cognitive probing approach

Abstract

The requirements for communicating ecosystem services (ES) information are often not considered in operationalizing ES concepts. In particular, the heterogeneous uses of ES require different functionalities and qualities for the information provided, which must be considered when processing ES data into different types of information. The relevant factors that influence the usability of ES information include the users' knowledge and cognitive ability as well as case study – specific factors. This missing knowledge can affect the transformation of the ES concept into practice, thus preventing the use of ES for further development or for transformation to sustainable management. Providing information that is relevant and useful for decision making thus depends on understanding potential users' demands and their cognitive processes involving the information in making decisions.

In this contribution, we present the evaluation of specific design features of a prototype ES decision support system assessed in an eye-tracking experiment. The study was conducted with more than 100 participants who were split into two groups. The participants in both groups had a background in spatial planning but differed in their connection to the case study region. The tool presented various GIS-based modeled land use scenarios driven by a new spatial planning policy recently adopted in Switzerland that lead to various impacts on ES in the region. The ES information was shown with additional land use indicators as well as information about the landscape aesthetic in landscape visualizations. The results show that there were significant differences between the participants in the way they perceived, interpreted and used the information for ES-based decision-making tasks. We also identified critical key factors defining the types of representation of the information that influence perception and cognitive processes.

In summary, the results of the study provide design recommendations for representing ES information based on the intended use and identify critical representation features that could potentially influence the perception of ES information.

5.1. Introduction

In 2011, the European Commission (EU) adopted the EU biodiversity strategy to halt the loss of biodiversity and Ecosystem Services (ES) in the EU by 2020 (European Commission, 2012). The EU strategy targets public awareness of ES issues in addition to establishing education and communication campaigns as well as developing instruments for more effective ES management and providing information on ES. These targets are crucial elements of sound decision making and therefore call for an improvement in and implementation of ES information in spatial planning tools and processes to provide ES-based reasoning and communication to stakeholders and the public. At the same time, the existing working group on Mapping of Ecosystems and their Services in the EU and its Member States (MESEU) has been investigating the best practices for supporting the improved implementation of ES information in policy and decision making (MESEU, 2014). To achieve the strategy targets by 2020, information on the ES provided at the local scale is indispensable for implementing the information in spatial planning. In terms of communication strategy, ES information can be provided in a wide range of different types and scales, but clear guidelines on which types or scales are suitable for conveying this information to various types of users is lacking (Klein et al., 2015).

A new trend is to provide the public with spatially explicit environmental information–for instance, information on provision of ES–via streamlined, easy-to-use and often web-based GIS platforms (e.g., www.ecometrica.com). Some of these platforms are specifically designed to provide relevant information in decision-making processes or to allow exploration of future scenarios (e.g., Wissen Hayek et al., 2015 and Grêt-Regamey et al., 2013). Such platforms are also known as planning support systems or decision support systems (DSSs). In landscape and urban planning such DSS can contribute to support sound decisions that account for sustainable use of ecosystems and their providing services. The trend of such DSS emergence has been stimulated by modern information and communication technologies and policy strategies, such as worldwide access to broadband Internet (also an EU initiative; European Commission, 2015a). Furthermore, EU policy aspires to provide cross-national spatial information: For example, the EU's Infrastructure for Spatial Information in the European Community (INSPIRE) aims at establishing common data typologies for transnational environmental assessments and environmental policies (European Commission, 2015b). In addition, national laws for the provision of and public access to spatial information were passed in recent years, for example, in Germany (BMUB, 2012) and Switzerland (GeoIG, 2007). With these regulations, access to environmental and ES information can also be enabled, allowing potentially easier use and implementation of administrative information in a DSS, which would facilitate transparency, credibility and legitimacy, as previous studies have shown (e.g., Wissen Hayek et al., 2015; Ruckelshaus et al., 2015; Pettit et al., 2011 and Cash et al., 2003).

Empirical studies in spatial decision making have shown that the amount of information affects the quality of the decisions (e.g., Jankowsky and Nyerges, 2001; Jelokhani-Niaraki and Malczewski, 2014). For example, as the number of alternative locations or criteria available in the decision-making process increases, stakeholders also need an increasingly deeper understanding of the relations and dependencies of the locations or criteria to assess and prioritize them (Jelokhani-Niaraki and Malczewski, 2015). Furthermore, recognition of relations and dependencies becomes more difficult, and users then tend to simplify their decision-making processes to avoid high cognitive demands for examining the information. Consequently, low-quality decision making and a low level of consensus between decision makers frequently occur (Jelokhani-Niaraki and Malczewski, 2015). Although the relevance of information integrated in a DSS facilitates the transparency, credibility and legitimacy of decision making (Ruckelshaus et al., 2015), the best methods for representing information so that the users' decision-making process is most effectively supported and the level of information required for high-quality decisions remain unclear.

In general, to communicate is to transmit information so that it is understood and, typically, used to guide action. For environmental information, the relation and interaction between different environmental criteria make successful communication a complex, multifaceted task. This complexity is further increased by spatial information, which makes comprehensive understanding and, therefore, effective communication more difficult (Mors et al., 2010). The initially communicated environmental information hinders easy information transfer because of the multifaceted effects on other environmental criteria. Especially, the communication of combined environmental and spatial information can lead to complex socio-psychological interactions (Mors et al., 2010), including emotional reactions if recipients are personally affected or have a relation to an affected place (e.g., Veríssimo and Campbell, 2015 and Rogge et al., 2011). As previous studies have shown, recipients can often cognitively link the communicated environmental criteria to landscape aesthetics (e.g., Junker and Buchecker, 2008). Such an extended perspective of non-DSS-included information (as they would be supported by landscape visualizations) can be based on either experience or knowledge of the place. These reactions can be identified over the course of participative landscape planning approaches in which stakeholders react and interact with provided information (e.g., Celio et al., 2014 and Höppner et al., 2007). In contrast, a lack of information or criteria that are used for reasoning can affect the trust or confidence in a DSS, as there is a lack of completeness. Disinterest in participation or dissatisfying communication might be the consequence (Höppner et al., 2007). Most notably, not only the detail, comprehension and amount of information (e.g., indicators, criteria and localities) influence user emotions and behavior, but also the design of the presented information affects cognition and therefore the reasoning processes (Russo et al., 2014). Consequently, understanding the information requirements of DSS users can result in more comprehensive and improved communication and thus more effective and efficient decision making due to the transparency, credibility and legitimacy of the information integrated in a DSS (Wissen Hayek et al., 2015, Ruckelshaus et al., 2015 and Pettit et al., 2011). In summary, to determine how to provide the most effective and efficient information for users, two main aspects must be addressed: how to communicate environmental and ES information comprehensively and how to represent such information. Knowledge of these aspects can avoid negative effects such as a loss of trust and confidence, or emotional reactions that prevent an objective examination of the information (Pettit et al., 2011). Especially for DSSs, appropriate communication and presentation of information are important to support users with relevant and needed information in their personal decision-making strategy (Jelokhani-Niaraki and Malczewski, 2015; Vessey, 1991 and Vessey and Galletta, 1991).

Novel techniques such as eye tracking (ET) make it possible to record humans' gaze and, thus, to research visual behaviors in a natural setting. With this technique, we can investigate how DSS users use information and apply a DSS. ET has been proven to be a helpful technique in user research, especially for the evaluation of visual stimuli in practical applications. With ET, the length and frequency that users look or gaze at particular areas of interest (AOIs) can be determined (Duchowski, 2007 and Holmqvist et al., 2011). The position of the gaze is typically expressed using screen coordinates (i.e., pixels). From these basic screen coordinate measurements, various gaze metrics are derived in relation to the stimuli (screen display), such as the fixation duration or dwell time (i.e., how long a gaze is fixed on a certain AOI), fixation count (i.e., how often the gaze fixed on an AOI), number of revisits (i.e., how often the gaze revisits an AOI) of the AOIs and scan-path characteristics (e.g., length and speed of eye movements; Ooms et al., 2014). Although a new technique, ET has already been applied in many research fields, such as software engineering (e.g., usability tests; e.g., Jacob and Karn, 2003 and Nivala et al., 2001), marketing (e.g., advertising placement, webpages, product label design; e.g., Goldberg et al., 2002, Pieters, 2008, Pieters and Wedel, 2004 and Poole and Ball, 2006), psychology (e.g., reading, scene perception, visual search; e.g., Rayner, 1998, Rayner, 2009 and Recarte and Nunes, 2000) and landscape perception and design (Dupont et al., 2013 and Duchowski, 2007). However, gaze behavior does not provide feedback about why DSS users focus on specific information. In other words, ET cannot be used to determine whether the visually perceived information is relevant for reasoning or decision making. However, a combination of ET and cognitive interviewing enables an investigation of usability of provided information. To understand this interaction between the use of information integrated in a DSS and cognitive processes, cognitive interviewing, which has been designed to capture cognitive processes and is supported by a large body of methodological research, must be applied (Campanelli, 1997, Campanelli et al., 1991, De Maio and Rothgeb, 1996, Dippo, 1989, Esposito and Hess, 1992, Jabine et al., 1984, Jobe and Mingay, 1991, Jobe et al., 1993, Lessler and Sirken, 1985, Royston et al., 1986, Sirken et al., 1999, Willis et al., 1999 and Willis and Schechter, 1997). Thus, by linking information provided by ET with knowledge of cognitive processes, users' manner of perceiving information provided by a DSS can be investigated.

With this study, we shed light on the usability of an ES-based DSS. We investigated what information is used and how this information affects users' cognitive processes and reasoning in decision making. We designed a DSS that displayed ES information in various types of representation. Further, we developed an experimental design based on *functions in application* of ES information (Klein et al., 2015) to identify key types of representation for communicating ES information. Various functions in application and various experimental tasks were defined that prompted users to apply the information integrated in the DSS in various contexts. These functions in application describe the differences between the purposes the users were applying ES information. Klein et al.'s (2015) results showed that users demand or prefer specific display types or types of representation depending on the intention for using the ES information and thus on the specific function in the application. In the present study, during the experimental runs, the users' gaze behavior was measured with ET to identify which ES information was used. We also developed a set of cognitive probing questions to investigate users' reasoning based on perceived information. Finally, to understand how users' attachment to a location influences their use of information, reasoning and decision strategy, we applied a split-sample design that separated users with and without connections to the region.

5.2. Methods

In the following section, we describe (1) how the ES information was presented by various types of representation integrated in the DSS and (2) how we determined specific user behaviors on the intention of applying the ES information. For the latter, we used ET parameters to analyze the participants' gaze characteristics in information use and cognitive interviewing to identify relevant information for certain decision making and reasoning. To combine the methodologies, we developed a set of probing questions, specifically tailored to the study's tasks. Further, information on the participants' connections to the case study region were also collected to investigate whether familiarity with the region affects reasoning and use of the ES information. The measured ET parameters were analyzed with a repeated-measures analysis of variance (ANOVA) and linked to feedback from the cognitive interviews.

5.2.1. DSS content and case study region characteristics

The region is characterized by increasing settlements in total area through an expanding secondary sector (+87 ha) and higher average spatial demand per person (+18% on average; BFS, 2015). The resulting land use conflict between fertile farming land and suitable settlement areas has led to a loss of ES and original landscape characteristics in the region, a development that could cause loss of attraction as a tourist destination (Brand et al., 2013). The landscape is further structured in small and often badly accessible or badly cultivable agricultural areas, especially in more remote areas. The most fertile and most accessible farming land is located at the bottom of the main valley directly adjacent to the city of Visp, which also recorded the highest increase in settlement area within the region (BFS, 2015 and VSGIS, 2015). In the peri-urban to rural surroundings of Visp, the primary sector is still the most important source of income other than tourism (Brand et al., 2013).

The case study region in the Canton of Valais, Switzerland, covers a total area of 348.8 km^2 and is home to 16,021 residents (as of 2013; BFS, 2015). The largest city, Visp, is located in the main valley, to which the valley of Saas is connected in the south and the valley of Baltschieder in the north (Figure 4). The valleys are surrounded by alpine terrain. The Rhone River flows through the main valley. Twelve municipalities are located within the region, all within the Visp district: Baltschieder (658 m a.s.l.), Einstein (1086 m a.s.l.), Saas-Balen (1483 m a.s.l.), Saas-Fee (1798 m a.s.l.), Saas-Grund (1559 m a.s.l.), Saas-Almagell (1672 m a.s.l.), Stalden (795 m a.s.l.), Staldenried (1052 m a.s.l.), Visp (658 m a.s.l.), Visperterminen (1378 m a.s.l.) and Zeneggen (1370 m a.s.l.). The one exception is the village of Eggerberg (846 m a.s.l.), which is in the neighboring Brig district.

The DSS shows changes in land use and ES under various socio-economic and climate scenarios in the region. Mountain cultural landscapes that developed during centuries and millennia are undergoing rapid transformation, leading to a growing loss of the ecosystem services (e.g. food production by agriculture) demanded by people living in and outside these areas. Whereas settlement expansion is nurtured by a better transportation infrastructure and the expansion of service and manufacturing industries, structural changes in the agrarian sector have led to an intensification of agricultural land use practices and the associated decline in semi-natural habitats. The content is based on model outputs generated by a modeling framework consisting of a spatially explicit agro-economic optimization model linked with a cellular automata based settlement allocation model. The GIS model couples agro-economic land allocation modeling and settlement expansion modeling to explore the effects of spatial planning instruments on ES provision. The modeling framework links two models: a recursive-dynamic agent-based land use model (the Alpine Land Use Allocation Model, ALUAM) and an automated settlement transition model (the Dynamic Settlement Allocation model, DSA). Both models are spatially explicit with a resolution of 100 m×100 m per raster cell. Based on a land use map as well as agro-economic input data, the ALUAM simulates land use changes and ES provision in agriculture and forestry under different sce-

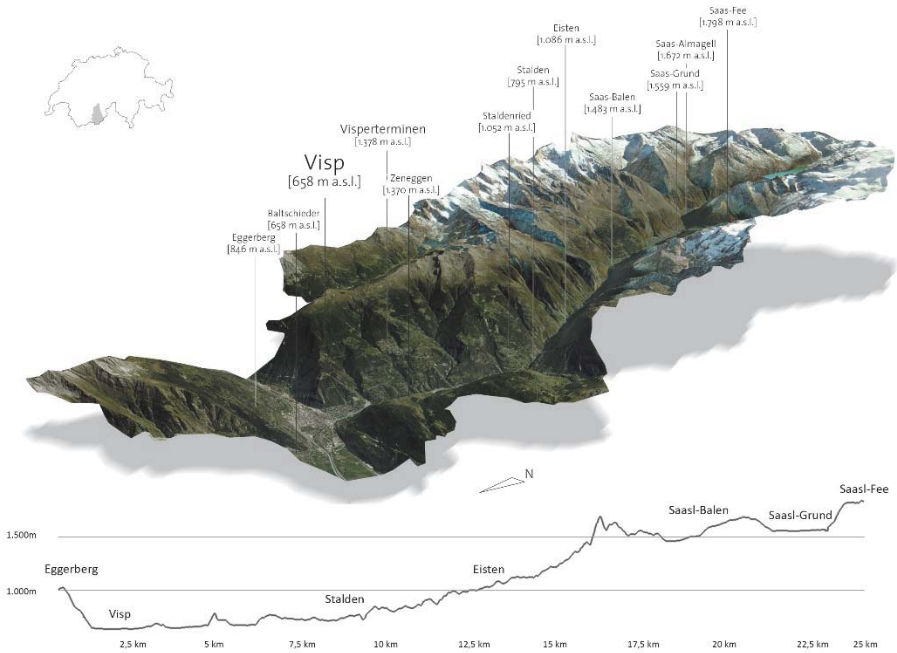


Figure 4 - Case study region, Visp district. The profile shows the bottom of the valley starting at the counter-slope in Eggerberg, down to Visp and upstream to Saas-Fee.

narios by maximizing the aggregated income of farmers and foresters in the region. The resulting land use map was subsequently transferred to the settlement allocation model DSA. The DSA then calculated the demand for new settlement area in the region and allocated the required number of settlement cells based on the location factors and the ES. The scenarios demonstrate that spatial planning is key for shaping mountainous landscapes and supporting ES. Cooperation among municipalities and an explicit consideration of ES can inform ES trade-off decisions under the pressing demand for land.

For this study, two scenarios were selected and visualized on the DSS. In scenario A, new settlement cells can be allocated freely adjacent to existing settlements, and municipalities are cooperating to distribute the new settlement cells. In scenario B, new settlement cells are allowed only in designated building zones.

5.2.2. DSS integrated types of representation

Based on Klein et al.'s (2015) work, an experimental design was developed to

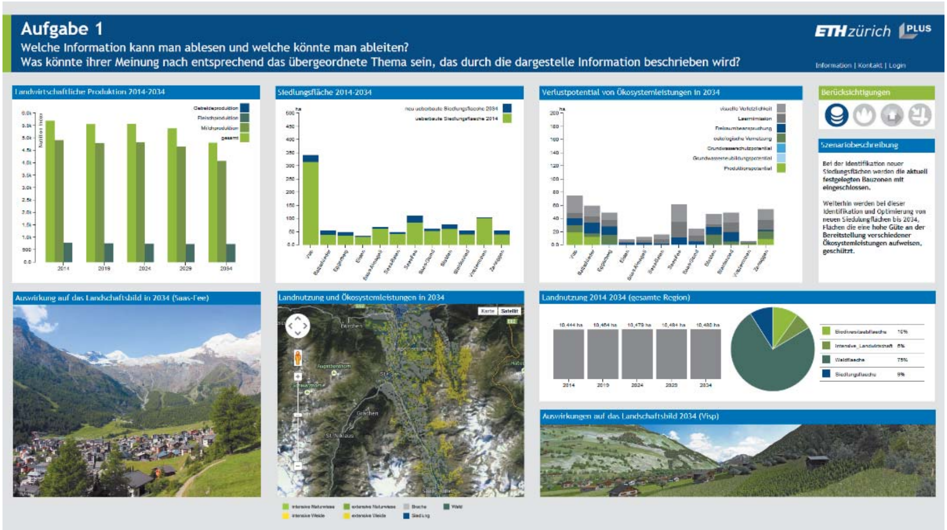
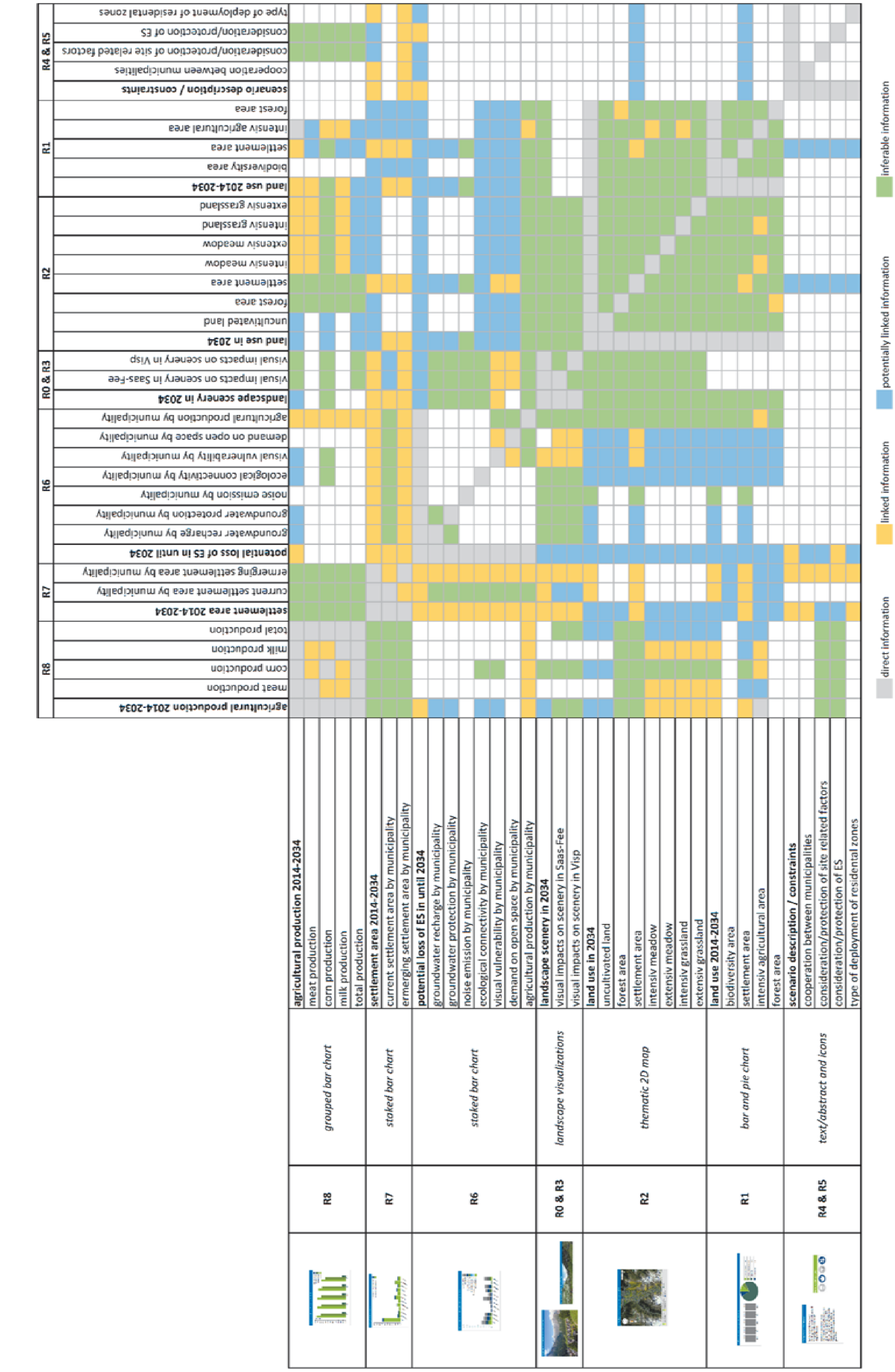


Figure 5 - Decision support system with ecological services information provided by various types of representation.

identify types of representation for communicating ES information. The method builds on analyzing participants' behavior while they use ES information. Figure 5 shows the DSS on a display monitor, which was used as the DSS user interface for the experiment.

All ES information in the DSS was available in more than one representation; thus, the participants could prioritize which representation type they want to use for different tasks. Table 4 shows how the information of the various types of representation was linked. *Direct information* (grey cells, Table 4) means that the specific information could be read out directly from a representation type, whereas *linked information* (yellow cells, Table 4) means that the same information content was also represented by another representation type. *Potentially linked information* (blue cells, Table 4) means that information can be connected to information from other types of representation in a more inferable way. Last, *inferable information* (green cells, Table 4) indicates that a deeper understanding of the data was required for further information gain. For example, by switching between the two scenarios the participants could have read that the settlement area was constant over the area but varied among the municipalities. Such varying settlement area deployment on municipal level also affected potentially different increases in noise stemming from increased traffic because of additional settlement areas in peri-urban municipalities. However, this information was not shown in the DSS, and participants had to be aware of the potential consequences of peri-urbanization to draw such a conclusion.

Table 4 - Links and interdependencies between types of representation and the information content.



All information describing or resulting from a scenario (e.g., scenario definition and constraints, ES loss and land use impacts) was grouped as AOIs, which were used as the units for the ET experiment (Figure 6). The AOIs corresponded to the main representation categories identified in Klein et al.'s (2015) demand analysis. The AOIs were comprised of visual and non-visual representations and covered similarly sized areas on the DSS screen, which consisted of eight AOIs. A *realistic landscape visualization* (R0) showed a view of a settlement area in the municipality of Visp in 2034. In addition to changes in the number of buildings, the visualization showed agricultural changes with different types of meadow (intensive vs. extensive use) varying in growth height and vegetation composition. Information on land uses over time from 2014 to 2034 in 5-year increments was provided by a combined *bar and pie chart* (R1). This information was available at the municipal and regional levels. Additionally, this representation allowed the participants to investigate either the total area of the land use type per time step or the proportions per year. Using this representation, the participants related information from finer scales (e.g., municipality) to the entire region. In a *thematic 2D map* (R2), land use information was presented as a raster map, which showed intensive and extensive meadows and pastures, as well as settlement areas, forest and uncultivated land on top of aerial images and thematic map layers. The participants interacted with this thematic 2D map by zooming and panning, for detailed inspection of the sites (e.g., investigate the location of the municipalities). In the *photorealistic landscape visualization* (R3), the municipality Saas-Fee in 2034 was shown. Between the scenarios, the number of buildings in this visualization changed. A short scenario description was provided as a *text/abstract* (R4) that contained information about the scenario preconditions. Additionally, scenario constraints were shown with *icons* (R5) for quick identification of the differences between the scenarios. The various icons were explained at the beginning of each trial. Furthermore, mouse-over tool tips were available for the icons. The potential loss of various ES (noise emission (recreation/quietness), visual vulnerability (aesthetics), demand on free space (recreation nearby), ecological connectivity (habitat function), agricultural production (food production) and ground water (protection, ground water recharge)) in 2034 was displayed as a *stacked bar chart* (R6) by municipality. The settlement area in 2014 and 2034, again differentiated by municipality, was also displayed as a *stacked bar chart* (R7). A *grouped bar chart* (R8) was used to depict the development of agricultural production in 5-year increments for various agricultural products (i.e., meat, crop, milk and total).

Data from the modeling framework was provided as an ASCII table. These data were either converted to a Key Markup Language (KML) map presented by Google Maps API (http://developers.google.com/maps) or linked to various chart visualization libraries using various D3js JavaScript libraries (www.d3js.org). KML and Google Maps were used for the *thematic 2D maps* (R2), whereas the diagrams (R1, *pie and bar chart* for the whole

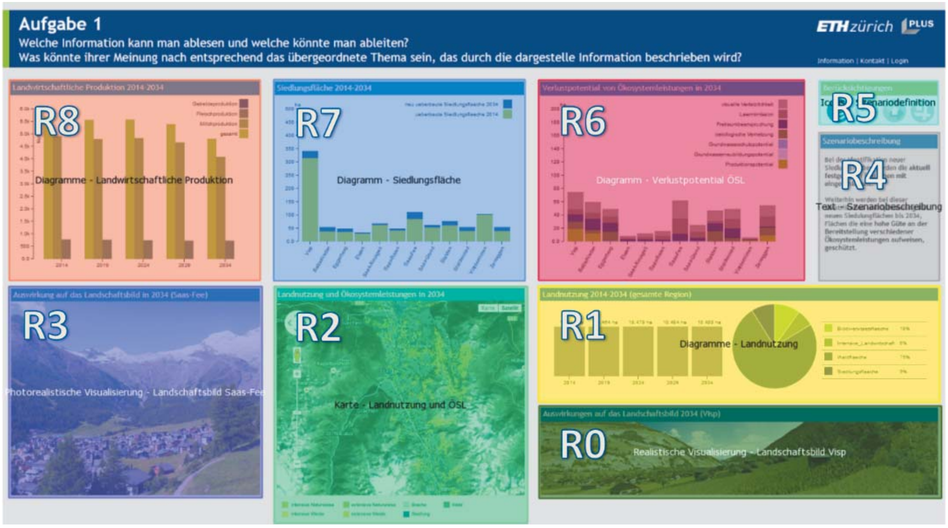


Figure 6 - Various types of representation (R0–R8) defined as the areas of interest (AOIs).

study region land use information; R6/R7, *stacked bar charts* for the potential ES loss, and current and new settlement area; R8, *grouped bar chart* for agricultural production) were generated with JavaScript. Both *landscape visualizations* were created separately with a photo montage in Adobe Photoshop (R3: *photorealistic landscape visualization*) or with 3dnature VNS software (www.3dnature.com), (R0: *realistic landscape visualization*). In addition, both landscape visualization types represented the land use characteristics of the modeled scenario data. The user interface was programmed in web-based HTML language. HTML-based tags contained the various types of representation.

5.2.3. Study sample

The participants (n=102) were university students who received invitations to participate in their classes and by e-mail. The study lasted from March to May 2015. The study participants were subdivided in two user groups: The first group (n=50) had no direct connection to the region and consisted of spatial planning or environmental science students from the Federal Institute of Technology (ETHZ) in Zurich, and the second group (n=51) consisted of persons with a direct connection to the study region or the region of Valais and were tourism students at the Haute école spécialisée de Suisse occidentale (HES-SO) Sierre. Both student groups had a common background in sustainable planning. All participants were undergraduates or had received a bachelor’s degree; 62.7% (n=64) of the participants were female, and 37.3% (n=38) were male. Most participants were between 21 and 30 years old (82.4%, n=84); only 6.9% were 20 years or younger (n=7). More than half (56.9%; n=58) of the participants had previous personal experience with the topic, and 52% (n=53) had worked on the topic as part of their occupation or studies. Nearly a quarter of the participants in the second group (24.5%; n=25) indicated that they personally or their family members or friends would be directly affected by the impacts of the scenarios.

5.2.4. Experimental design

To cover a broad set of *functions in application* (i.e., the intention to use the information as described by Klein et al. (2015)), a set of nine tasks (nine stimuli) was defined to analyze how users applied the ES information integrated in the DSS when they faced a question to which the answer could be derived from the information. The definitions of the possible basic functions of ES information in the DSS are based on Brömmelstroet (2013) work and consist of informing about, communicating and analyzing content, which also describes the intention to use the information integrated in a DSS. In a previous study (Klein et al., 2015), we developed a more detailed set of these *functions in application* to differentiate among the detailed properties of various demands (e.g., *exploration of content, spatial analysis, support of assessment*, Table 5). With these more concrete *functions in application*, it becomes possible to understand the relevant stages of individual reasoning and decision-making processes (Klein et al., 2015, Keller, 1997 and Simon, 1960; Sugumaran and de Groote, 2011). Table 5 shows the tasks participants were exposed to with the related *functions in application*.

All participants were shown a sequence of web-based HTML screens starting with a welcome site, an ET calibration site, and a thematic introduction, followed by experiment instructions and background information on the information by types of representation. The participants started each task whenever they were ready. As a reminder, the tasks were presented at the top of the DSS screen. The information was shown for only a limited time. During these time sequences of 2–4 min (depending on the task), the participants were asked to derive the answer for a task by concentrating on the information without talking to the study attendant (with exception of Task 2). After the set amount of time, the DSS and its information panels disappeared, the task or question was repeated and the participant was asked to answer. In addition to the main question of the task, two to three questions were asked to identify the participants' cognitive processes and to understand their reasoning (see Section 5.2.5.2). Depending on the specific task, information on a second scenario was also available on a second screen, and the participants were allowed to switch between the screens. The task sequence was randomized, with the exception of Tasks 1 and 9 (Table 5). The data gathered in Tasks 1 and 9 were not considered for the ANOVA, because these data had either an introductory or control function. The complete study re-

Table 5 - Definitions of tasks based on the functions in the applications.

ID	Function in application	Task	Time	Scenario number
Task 1 (T1)***	Content information	What information can be extracted or inferred from the DSS? What might the overall topic of the information?	4'	1
Task 2 (T2)**	Communication of content	Please describe the scenario characteristics.	2'	1
Task 3 (T3)*	Exploration of content/ support of analyses	Please show how the scenarios vary. How do you interpret this difference(s)?	2'	2
Task 4 (T4)*	Support for spatial analyses	In which locations are the biggest difference(s) between the scenarios?	2'	2
Task 5 (T5)*	Support for estimates/ scenario development	Please estimate how the scenarios would result if there were no new settlement area in the municipality of Visp in 2034.	2'	2
Task 6 (T6)*	Support for assessment	Please assess the impacts of the new settlement areas in 2034 on the municipalities of Saas-Fee and Visp.	2'	2
Task 7 (T7)*	Support for aesthetic assessment/decision-making	Please assess and decide which scenario provides the most beautiful landscape.	2'	2
Task 8 (T8)*	Support for decision-making	Please assess and decide for this scenario which one is the most ecologically sustainable.	2'	2
Task 9 (T9)****	Support for aesthetic assessment/decision-making	Please assess which of the scenarios provide the most beautiful landscape.	30"	2

* Randomly deployed in the experiment sequence between T1 and T9

** The participant was asked to explain simultaneously while the information was shown the scenario characteristics to the study attendant.

*** Introduction function to allow participants to initially identify what the topic is about with the information

**** Control function to identify differences in application characteristics between realistic and photorealistic landscape visualizations. Only representation type R0 (the realistic landscape visualization) and R3 (the photorealistic landscape visualization) were shown on the screen; they showed the same perspective of a settlement area of municipality Visp. For this task, both types of representation (R0 and R3) were displayed at the same time for both scenarios. Fig. 7 shows the two scenarios in different types of landscape visualization that varied in the level of realism next to each other.

quired 40–60 min per participant, depending on the rate and complexity of the answers. The total time that the information screens were presented to the participants was 18 min 30 s (Table 5).

5.2.5. Data acquisition, processing and analysis

5.2.5.1. Eye tracking

In the study design, the participants were asked to wear mobile SMI ET glasses (www.smivision.com) to capture gaze behavior when they looked at the DSS information on a 24 in. 16:9 monitor display with a resolution of 1920×1080 pixels. The ET glasses were a binocular eye tracker, which captured both eyes and computed the gaze position in a scene image. The scene image was captured by a scene camera located in the center of the glasses. To obtain accurate gaze positions, each participant had to perform a system calibration. The ET glasses measured the gaze pointer for both eyes with automatic parallax compensation with 30 Hz. Gaze pointer accuracy of 0.5–1.0° and a tracking range of 80°/60° horizontal/vertical assured the precise localization of the participant's gaze on the 1280×960-pixel scene video with 24 fps that was captured by the ET unit.

BeGaze™ analysis software by SMI (www.smivision.com) was used to process the raw ET data generated in the experiment. With BeGaze™, we calculated the variables *dwell time*, *fixation count* and *revisits* of the AOIs, which were also used in the statistical analyses as suggested by Ooms et al., 2014, Dixson et al., 2014 and Vidal et al., 2013. The number of revisits of an AOI indicates its complexity: Users have to revisit the AOI repeatedly to link, analyze or compare the presented information together with other information. Dwell time and fixation count quantify the use of AOIs for the task at hand and identify the potential relevance of the information for answering the task question.

5.2.5.2. Cognitive interviewing

Cognitive interviewing is a general method that critically evaluates the transfer of information (Willis, 2005). So that respondents understand the questions correctly, technique and question design are important for cognitive interviewing. Think-aloud and verbal probing approaches assume that participants can report and even evaluate their own cognitive processes (Willson and Miller, 2014). However, the think-aloud method in combination with ET has been criticized (Oh et al., 2013). Verbal probing uses an afterwards/debriefing survey design that is more suitable in combination with ET and is appropriate for cognitive and decision process investigations (Caspar et al., 1999 and Willson and Miller, 2014). Therefore, we decided to apply the verbal probing method.

In the debriefing survey, we included the four questions presented in Table 6. In the *recall and construct strategy* question, we asked for an explanation. To identify the overall ability and experience of using ES information to fulfill a task, in the *comprehension question* the participant was asked whether completing the task or answering the question was difficult and to identify his or her overall ability and experience. The participant rated the question on a binary scale ranging from *difficult* to *easy*. The *confidence identification* ques-

Table 6 - Cognitive probing question set by tasks (stimuli). Translated from German.

ID	Recall and construct strategy (1)	Comprehension identification (2)	Confidence identification (3)	Term interpretation (4)
Task 1	Why do you think this is the topic described by the information?	Was the question easy or difficult to answer and why?	How certain are you that this is the topic for which the information is provided?	-
Task 2	-	Was the question easy or difficult to answer and why?	How certain are you that you have communicated the scenario correctly?	-
Task 3	Why did you interpret the differences in this way?	Was the question easy or difficult to answer and why?	How certain are you that you interpreted the differences correctly?	-
Task 4	Why do you think that the biggest changes or impacts can be found specifically in these locations?	Was the question easy or difficult to answer and why?	How certain are you that you identified the locations with the biggest changes or impacts?	-
Task 5	Why exactly do you think that these would be the impacts?	Was the question easy or difficult to answer and why?	How certain are you of your estimates that these would be the consequences?	-
Task 6	Why exactly do you think that these would be the impacts?	Was the question easy or difficult to answer and why?	How certain are you about your assessments that these would be the impacts?	-
Task 7	Why do you think that the chosen scenario provides the most beautiful landscape?	Was the question easy or difficult to answer and why?	How certain are you that you have really chosen for the scenario the most beautiful landscape?	What do you understand under "beautiful landscape"?
Task 8	Why did you think that the chosen scenario is ecologically sustainable?	Was the question easy or difficult to answer and why?	How certain are you that you really have chosen the most ecologically sustainable scenario?	What do you understand under "ecologically sustainable landscape"?
Task 9*	Why do you think that the chosen scenario provides the most beautiful landscape?	-	-	-

* Task 9 is defined as a control task to identify potential bias of the landscape visualization types (realistic vs. photorealistic) (see Table 5, Fig. 7)

Figure 7 - Controlling task (Task 9) for identifying possible bias through the level of realism of the landscape visualizations.

tion was posed to identify the participant's confidence to investigate if and potentially why there were issues in fulfilling the task. The participants answered according to a 4-item Likert scale: *not at all sure*, *not sure*, *sure* and *very sure*. When the task included special terms (e.g., Tasks 7 and 8), we used another question to investigate the participant's term comprehension interpretation to identify whether there was bias through an incorrect definition or even a misunderstanding.

The participant's answers to the recall and *construct strategy question* were recorded in a protocol. In this protocol, all rationales by participants were collected and assigned to types of representation (AOIs) or further categories. For example, if the participants reasoned concretely by AOI assignable information, indicators or characteristics or stated therefore that he or she perceived this information by a specific AOI, the reasons were linked to these AOIs within the protocol. Furthermore, the various characteristics, elements and scales of the information provided by the different types of representation were protocolled (e.g., buildings, trees). We added a group of other scales that included extended region, if the participant wanted to reason by facts of outside the region at a larger spatial scale. We also added a group of *specific other locations*, if the reasoning was related to specific locations outside or inside the region. Other scales were *elevation-based location*, if the participant's rationales were based on altitude, and *thematic-based location*, if the participant related the location to specific areas that were defined by another topic (e.g., "everywhere there, where…"). These additional scale categories seemed necessary to compare the participant sample groups, as the participants with connections to the region could potentially have based their rationales on their knowledge of the place. Another category *other rationales* was added, if the participant's reasoning was not based on the DSS information or indicators. Figure 7.

5.2.5.3. Statistical analysis

For each of the ET parameters *dwell time, fixation count* and *revisits*, we compared the average value per representation type and task. We used a repeated-measures ANOVA with IBM SPSS Statistics version 22 (www.ibm.com/spss), in which the participants were entered as random effects, because repeated measures were performed per participant (i.e., each participant fulfilled all nine tasks by using the types of representation). Additionally, we compared differences in the average ET parameters between the groups with and without a connection to the region. To determine the attractiveness of the types of representation, we also investigated the cognitive interview protocols with a descriptive analysis.

5.3. Results

The results show that there are specific preferences in using ES information provided by types of representation. This user behavior depends on the function in application of the ES information. In other words, the intention of information use determines the preference for a certain representation type. For example, visual information in general was more preferred compared to texts or abstracts. To answer general questions, information presented on a small scale was preferred to large-scale information. However, information on a large scale and therefore more detailed information could improve the quality of the answers. The participants' connection to the site often influenced their reasoning and therefore the use of the scale of information. Such effects depend on the information depth and detail provided by a representation type and on the experience that participants have with specific types of representation, as well as the availability to link their knowledge of the place to the information provided. Participants with a connection to the region for which the ES information was provided exhibited other behavior than participants without a connection to the region. This effect was also identified in the cognitive interviews.

5.3.1. Eye tracking

Depending on the information necessary to solve a certain task, participants exhibited different strategies for acquiring relevant information, by using the various types of representation. Figure 8 shows this different use of the types of representation by task. This behavior varied for all tasks, and strong diversity in the preferred information by types of representation existed. Knowledge of place further affected the participants' reasoning and decision-making strategy.

The ET data showed a significant relationship between tasks and types of representation (Figure 8; Huynh-Feldt's sphericity test (dwell time: $p=0.363$; fixation count: $p=0.398$; revisits: $p=0.487$)). The univariate analysis results for the ET parameters of the types of representation (AOIs) showed high dependencies on tasks and therefore preferences depending on the intention to use ES information (dwell time: $p=0.000$, $F=26.888$, $df=17.410$; fixation count: $p=0.000$, F=27.757, df=19.117; revisits: p=0.000, F=22.093, df=23.385). Because the results for the ET parameters dwell time and fixation count (Table A2 and Table A3 in Appendix II) were almost identical, we focus on dwell time in the following paragraphs.

The value of revisits of an AOI can be seen as an indicator of the complexity of a representation type. It can be inferred that if a representation type contains either comprehensive information or the information is difficult to remember, participants revisit a representation type more often. However, it is remarkable that types of representation with a high revisit count were preferred for specific tasks although the required information was available from other types of representation with a lower revisit value (i.e., types of representation that were easier to read). Consequently, it seems that the complexity of the ES information does not discourage participants if it is in line with their intention to apply the DSS (*function in application*).

The following results indicate that the participants also made assumptions about the effectiveness of the types of representation. This was particularly influenced by titles of types of representation, from which the participants interpreted their relevance for the tasks. For example, the titles for R0 and R3 were about landscape scenery, but R6 included information about landscape aesthetics. In contrast, R0 and R3 were limited by their information but were preferred for Task 7. This behavior seems to have been based on experience or expectations of representation type's title or even characteristics. The participants reported afterward that they had estimated, because of the time limitation, from which representation type they could receive the most supportive ES information to answer a task-specific question. Especially, such behavior was identified for Task 4 and Task 7, where *thematic 2D map* (R2) for a spatial analysis and *landscape visualizations* (R0 and R3) for an aesthetic assessment/decision making were mostly used. The most supportive information for both tasks was provided by the *stacked bar chart* (R6) that contained the indicator about the visual vulnerability, whereas the information content of the preferred types of representation used for the tasks was either limited to a location (R0 and R3) or consisted of generic land use information (R2).

Further, interactive types of representation, for example, provided by *interactive pie and bar chart* (R1) and *thematic 2D map* (R2), were not used above-average. The interactive functionality of these two types of representation was used only if the participants recognized the relevance for specific tasks, as it was given by Task 4 (*support of spatial analysis*).

Finally, texts/abstracts were the most unappealing types of representation. R4 and R5 consisted of texts or abstracts, and we observed that specifically for these types of representation the dwell times were shorter than average (Figure 8). However, in this study both types provided important information about the scenario conditions; the texts explained the scenarios (R4) and therefore provided

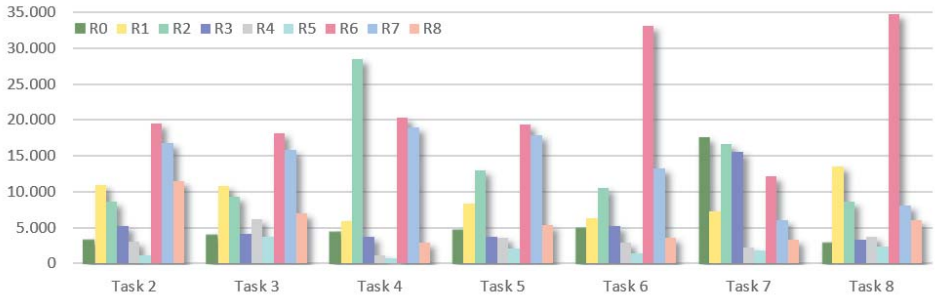


Figure 8 - Estimated mean dwell times [ms] for the types of representation separated by tasks, n=101 (n=50 without/ n=51 with a connection to the case study region).

easy differentiation between the scenarios. Even in Task 2 (*support of communication*), in which the participants were asked to communicate the scenario story face-to-face while the information was displayed, the text was mostly ignored. The same occurred for Task 3 (*exploration of content*), on which the participants had to explain the differences between the scenarios: R4 and R5 offered directly the required information but were mostly ignored.

For all tasks with the exception of Task 7, significant differences in the dwell times of the types of representation between the sample groups were identified (Figure 10). For face-to-face communication (Task 2), participants without local knowledge used significantly more generic information provided by the types of representation on a small display scale (R1, R4–R6). In contrast, the participants with a connection to the region preferred types of representation that provided location-specific ES information (R0, R3, R2). For scenario exploration or analysis (Task 3), participants with no connection to the region and therefore without local knowledge used the scenario descriptions (R4) and information about the potential ES loss (R6) to a significantly higher degree than the participants with local knowledge. This user behavior seemed to be contradicted by the data on spatial analysis in Task 4. However, this behavior can be explained by a lack of local knowledge: Participants without local knowledge spent more time with the map (R2) overall as they first needed to locate the municipalities before proceeding with information required to solve the original task (R7, R6). This effect can be also identified for Task 6 and the impact assessment of two municipalities (Task 6). The participants without knowledge of the location were required to initially locate both municipalities in the region before they performed a comprehensive assessment. A similar effect can be identified for the estimates of the indicators that were not represented and scenario development (Task 5), where participants without a connection to the region relied significantly more on information about the current and future sizes of the settlement areas within the municipalities (R7), as it explains a triggered event for potential ES loss (R6). In addition to the map (R2), landscape visualizations (R0, R3) were preferred by the participants without knowledge of place, whereas participants with a connection to the region used information that was not provided by the DSS significantly more (R8). At least for decision making (Task 8), participants with a connection to the region also considered aesthetic information (R3) significantly more than participants without a connection. Thus, participants with a connection to the region tried to more comprehensively use the information and included rationales that were not provided by the DSS triggering a comprehensive and more complex cognitive process (compare Task 2) than participants without a connection. This characteristic of task-specific preferences in ES information emphasizes the heterogeneous user demands due to their knowledge of place and therefore the resulting reasoning or decision-making strategy (see Section 5.3.2).

We also identified that participants generally spent more time on the *photorealistic landscape visualizations* than on the *realistic landscape visualizations* as identified by Task 9 (Figure 9, see also Figure 5). The reason for this participant behavior was the level of detail in the visualizations and therefore the number of visualized landscape elements and the time required to identify them. However, landscape visualizations with a higher level of detail supported improved landscape recognition as the participants with a connection to the region more easily identified the location presented by the photorealistic landscape than by the realistic landscape as was reported in the cognitive interviews.

More details about the differences between the participant groups and the ET variables are given in the tables in the Appendix II.

5.3.2. Cognitive interviews

Results of the cognitive interviews showed that the participants' reasoning strategy was task specific. As with the eye-tracking study, in the interviews, we found that certain types of representation were preferred for specific tasks, because the participants reasoned by concrete information characteristics that were provided by only a single type of representation. Rationales brought up in the interviews often related to the scale of the preferred information. Interestingly, especially participants with knowledge of the location reasoned about the scales and with information/indicators that were not provided by the DSS although relevant information was provided to answer the question. Such a deviation from the provided information reflects that integrated ES information in the DSS potentially triggers the direction of the cognitive process and shows simultaneously that not all relevant topics were or even could be provided by the DSS that are required by participants for reasoning or decision making.

Results of the cognitive interviews supported the results provided by the ET experiments; participants with a connection

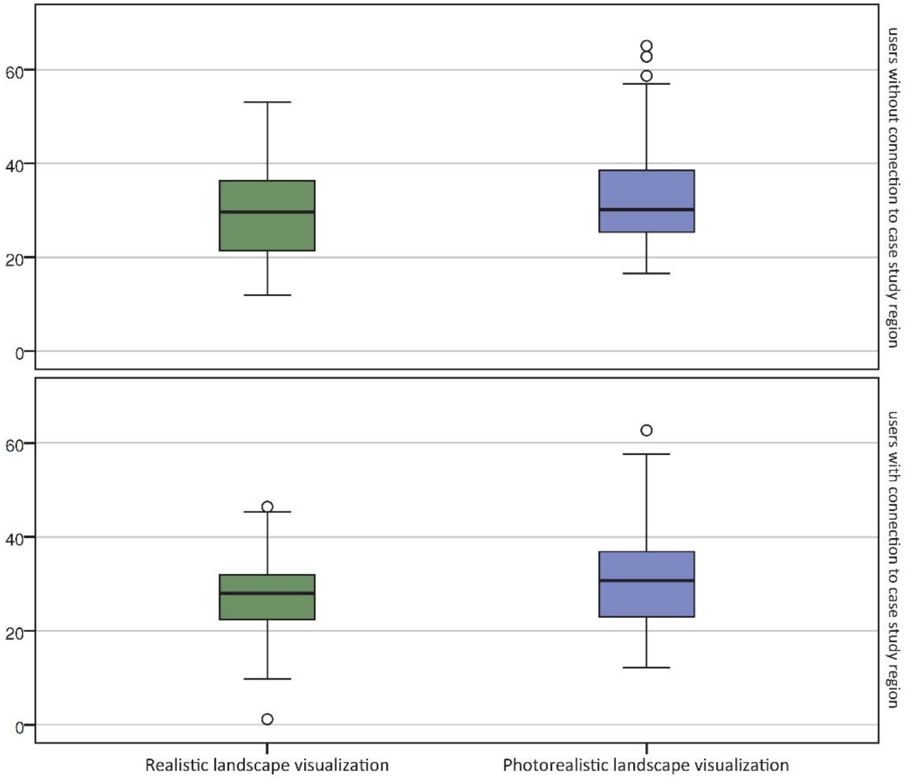


Figure 9 - Differences in using [dwell times in ms] landscape visualization types (R0 and R3) and therefore preferences in level of detail between the participant groups.

to the region generally reasoned more often with information not provided by the types of representation (12.66% of the total reasoning was based on other information) than the participants who had no connection to the region (only 4.2% of their total reasoning was based on information not provided in the DSS). In addition, the scale selected by the participants varied. Participants with local knowledge preferred the municipality scale (59.62% of reasoning) and other scales (6.69%). Participants without a connection to the region reasoned less about these scales in total (*municipality scale*: 54.33%, *other scales*: 3.91%) but used more general information about the total region as scale of reasoning (32.98% of total reasoning, compared to participants with connection: 25.11%).

The reasoning for aesthetic assessment and aesthetic decision making (Task 7) varied considerably between the participant groups. Participants without a connection to the region reasoned more based on aesthetic values provided by the landscape sceneries (R0, R3), whereas participants with local knowledge used the potential loss of ES in municipalities (R6) for reasoning. This reasoning strongly varied between the two participant groups by non-explicit aesthetic decision making for selecting the more sustainable scenario (Task 8). Here, participants with a connection to the region reasoned about the municipality scale in combination with scenario description (R5) and about indicators that were not presented, whereas participants without a connection to the region based their reasoning on the potential loss of ES (R6).

Using cognitive probing questions, diversity in knowledge/experience (comprehension identification) and understanding (confidence identification) were identified between the participant groups. Statistically significant differences existed between the participants' ratings for the level of difficulty for fulfilling a task, as well the belief in their reasoning. For example, in Task 2 (communication of content) both groups rated their confidence in their reasoning. Participants without a connection to the region considered this task to be easier than participants with local knowledge (mean value difference=0.304, p=0.027, t=2.237). Task 4 (support of spatial analysis) also showed very significant differences between the groups in the difficulty of fulfilling the task. Participants with a connection to the area rated this task as easier than participants without (mean value difference=0.268, p=0.004, t=2.947). Both significant differences can be explained by differences in local knowledge: In Task 2, participants with local knowledge exhibited more complex thinking and tried to consider other aspects than those provided by the DSS. However, they struggled to communicate about the scenario and their thoughts. This changed in Task 4, where local knowledge helped the participants directly analyze and infer spatial differences more comprehensively and complexly with *other rationales*, as opposed to participants who had no connection to the study area who had to spend time locating the municipalities first.

An investigation of the ET results compared with participant reasoning determined by cognitive probing (compare Figure 10 and Figure 11) illustrates that types of representation that showed information on a smaller scale were generally used to answer general questions about the region. For example, charts with information about the total region were preferred instead of information grouped by municipality, or to define the ecologically more sustainable scenario in Task 8, participants compared the total land use information with potential ES loss by municipalities. More details about the differences between the participant groups and cognitive protocols are given in the tables in the Appendix II.

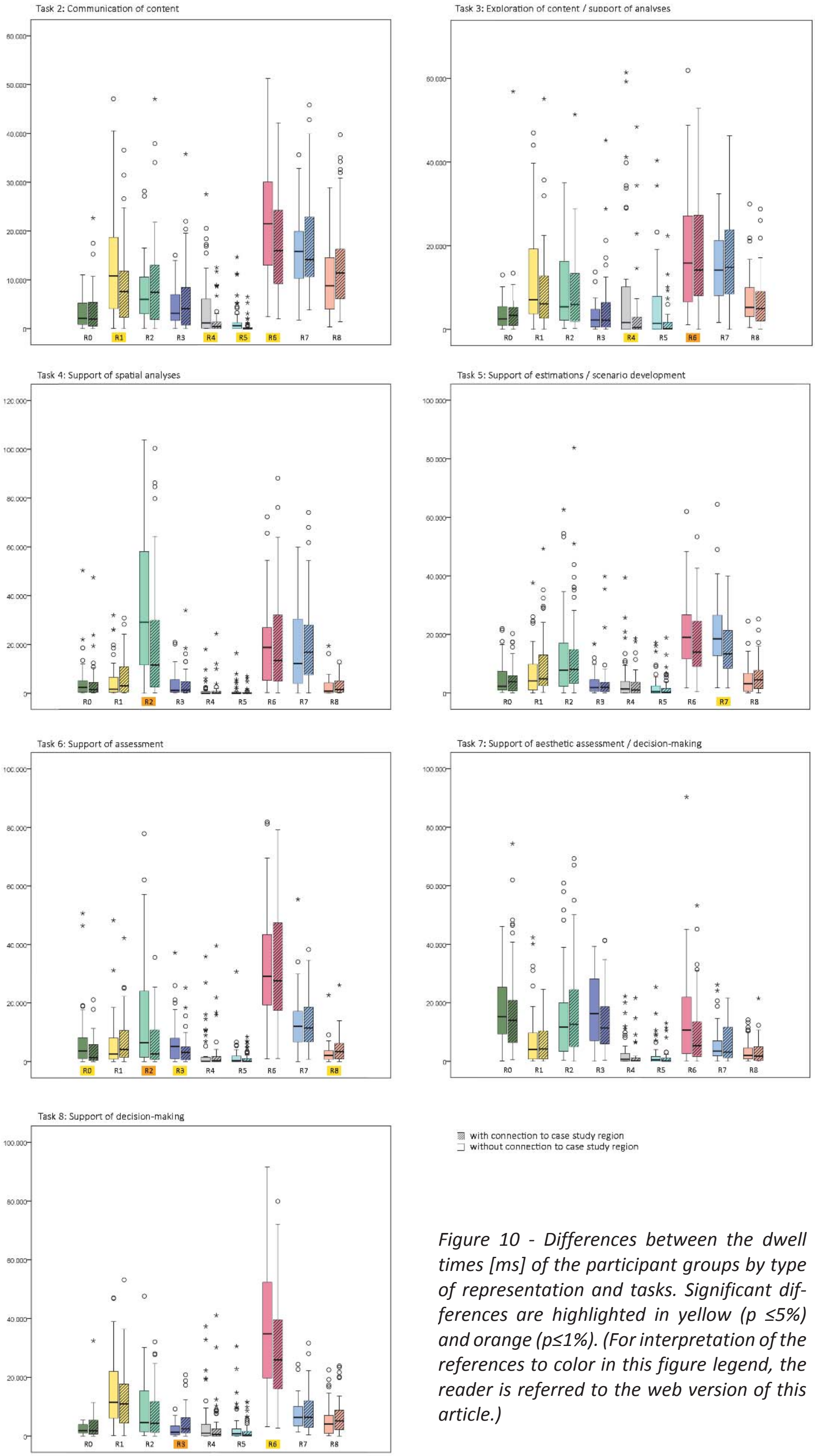
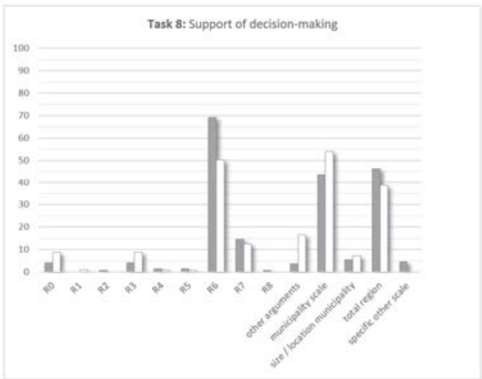


Figure 10 - Differences between the dwell times [ms] of the participant groups by type of representation and tasks. Significant differences are highlighted in yellow (p ≤5%) and orange (p≤1%). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



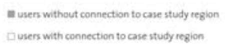


Figure 11 - Bar plots showing the percentage of times that participants indicated which representation type (R1–R8) and additional factors were reasoned to solve certain tasks (Tasks 1–8).

5.4. Discussion

We found heterogeneous participant preferences for ES information presented in various types of representation. The specific demands for ES information to solve certain tasks–and therefore the ES information's function in application (Klein et al., 2015), as defined in our study–reflect the complexity of providing (decision) supportive information. However, a combination of various types of representation allowed the participants to customize the ES information in such a way that their personal preferences were met. This potentially led to a bias in using types of representation that were personally preferred but actually provided less supportive information for the task at hand. Participants may even have relied more heavily on less relevant information for decision making because they chose the representation type based on its visual attractiveness instead of information relevance. Specific types of representation were preferred for certain tasks.

In particular, participant preferences for relying on types of certain ES information were context sensitive. Aspects that influenced participants' preferences and how they applied the available information included the topic of information, the reason why it was provided, the presented indicators and the details and scale of the information. Participants recognized situations in which needs and interests were not fully and clearly identified (e.g., Pettit et al., 2011 and Bartke and Schwarze, 2015). If the ES information was not considered supportive, the participants ignored it for reasoning and decision making. Instead, they relied on their experience and knowledge to bring in additional information that was not provided in the DSS. This effect was also described by Coussement et al. (2015); they concluded that a DSS that does not fully exploit all available information and neglects relevant information is unlikely to lead to optimal decisions. The authors also concluded that the opinions of experts, who are often the end participants in a DSS, must be heard during the design of the DSS to ensure that their needs are met. However, omission of information is not entirely inevitable and reflects the individuality of cognitive processes (Caspar et al., 1999). As our results show, there was no total individuality in the participants' cognitive processes. We identified differences between the participant groups and their reasoning as dependent on the participants' connection to the region. In addition, the availability of local knowledge seemed to affect decision making. Participants with knowledge of the location based their rationales more on information not provided by the DSS, scales and even political issues, while using the ES information integrated in the DSS as a trigger to think or discuss about further impacts in the region. Natarajan (2015) emphasized the ways participants bring in this local knowledge for reasoning in participatory spatial planning. This reasoning of locals is often very detailed and explanatory based on personal experience (Natarajan, 2015). Thus, the cognitive processes and reasoning of the participants with a connection to the region were often more complex or included political rationales.

The visual complexity and therefore the reading, understanding and remembering of the information provided by the representation type also influenced its uses. Studies have shown that visual complexity and design influence participants' perception, preference and behavior (e.g., Machado et al., 2015 and Quispel and Maes, 2014). In the present study, graphical information was used more than non-graphical information (for instance, text information). Although the text elements contained important information about the scenario, participants mostly ignored the text. With this behavior, scenario descriptions in R4 and R5 by DSS participants were ignored and therefore mostly not considered for reasoning, which shows that the participants were not able to weight the importance of the information. This behavior was likely based on retrospection, which means that visual information, for example in charts, is easier to remember and to compare than text and numbers. Dilla and Raschke (2015) concluded that specifically graphical representations are more efficient and effective for spatial tasks (i.e., assessing relationships among data), while textual representations are more efficient and effective for symbolic tasks (i.e., extracting individual data values). Depending on the intention of the applied information, scaling, categorization and filtering of information clearly affect the frequency of use of a certain representation type. This behavior can be explained by cognitive cost-benefit theory, which poses that more efficient and effective decision making results are accomplished when the problem representation matches the task (Vessey, 1991 and Vessey and Galletta, 1991). Participants make compromises either in the complexity of reasoning or in the spatial scale of their reasoning, if the information does not entirely meet their demands. This behavior shows that DSS users are biased by the display scales of information. Thus, they find thinking on other scales or even "outside the box" by extrapolating or transferring information limited to municipalities and their characteristics to correlated indicators or dependent place specifications difficult. However, information about the region on a small display scale was used to analyze the proportions of the ES information by municipality in a larger scale context. For example, the participants struggled with the overall statements about the ES loss for the region, because this information was provided only by municipality, not in total for the region. Therefore, they reasoned only on a municipality scale about ES loss or instead used information provided on a regional scale. If they used other information for reasoning about ES loss, they often failed to infer and consequently link this information to ES, though. This behavior was also observed in the use of complex types of representation. If these types of representation comprised indicators that matched the information requirements for the specific task, they were used although they were more complicated to read. For example, the information about ES loss was, compared to the other types of representation, more difficult to read and to compare to the other information. Nevertheless, the participants employed this information because they had recognized its importance, and this was the only representation type that displayed the required information directly. Otherwise, if the participants did not want to refer to this representation type, they were forced to infer information about ES loss from other types of representation, which required a more complex cognitive process. Such user behavior supports Vessey's (1991) cognitive fit theory, which is a special case of the cognitive cost-benefit theory in which it specified that decision makers choose strategies that trade off the effort required to make a decision versus outcome accuracy (Beach and Mitchell, 1978 and Payne, 1982).

The results showed that the participants used varying behaviors when they applied the ES information. These behaviors were mostly identified by the DSS participants with knowledge of the location. This local expertise led to alternative decision making by using the information provided as a trigger while basing their reasoning on other information. Identifying or existing knowledge consequently influenced this decision-making strategy. Figure 12 shows the decision-making model based on the results in combination with the cognitive fit and cognitive best-fit theories (Vessey, 1991; Vessey and Galleta, 1991) and alternative decision-making strategies. Depending on additional constraints (e.g., time pressure to accomplish a task/making a decision), the participants chose between accuracy-optimized and effort-optimized decision making. It seems that users depended their type of decision making on their expertise, difficulty of tasks, or knowledge where to find the relevant information in DSS. Due to these factors, users were potentially stressed (i.e. effort-optimized) because of limited time frame and choose the type of decision making individually. However, if the provided information did not match the cognitive notion, the participants mostly tended to develop an alternative decision-making strategy (non-solid arrow, Figure 12). Finally, there was still the possibility that the participants did not want or were not able to make a decision due a lack of information, which led to inconclusiveness.

Providing additional supportive information could avoid precarious user reasoning and consequently support better decision making. Although the amount of provided information may not be the critical factor in decision making, an increase in information could influence the evaluation process (with more demand on time) and could therefore influence cognitive loops during decision making (Jelokhani-Niaraki and Malczewski, 2014).

The amount of information in general influences a user's gaze. Results of other eye-tracking studies showed that fixation count and dwell time increased strongly with the number of AOIs (Vu et al., 2016, Horstmann et al., 2009, Lohse and Johnson, 1996 and Reutskaja et al., 2011). In addition, the amount of information is a critical aspect that could lead to an overload of information in a DSS and consequently overstrain participants. In fact, it is unclear how the gaze data were biased in this study, because not all provided information was directly relevant or further used for reasoning. Additionally, time pressure (as was the case in this study) affects gaze behavior and therefore decision

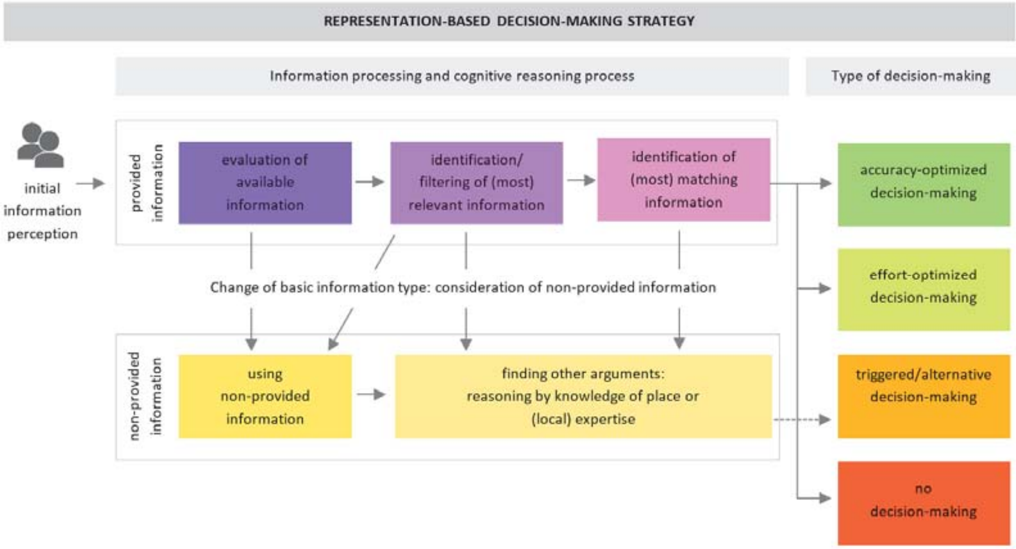


Figure 12 - Extended model of a representation-based decision-making process with alternatives strategies based on Vessey's (1991) and Vessey and Galleta's (1991) cognitive fit and cognitive best-fit theories, respectively.

making (Reutskaja et al., 2011). To avoid biased results through time pressure, we randomized the order of the tasks, and the AOIs were identical for all tasks. However, despite the unclear effects of time pressure, the results still show a diversity of participants' preferences in using ES information. The information provided did not change with the tasks, and Task 1 allow the participants to become acquainted with the information.

The present study underlines the complexity of environmental communication and information provision. Especially for setting up a DSS, consideration of user demands is crucial, and relevant information must be integrated. For identifying and understanding these heterogeneous user demands and behaviors, requirement engineering approaches such as usability tests with ET are important and helpful (Klein et al., 2015). A demand analysis should be performed initially to identify user-relevant information, especially if there are heterogeneous user groups. Otherwise, DSS users are likely to ignore the provided information and not use it for reasoning. Instead, they use the provided information only as a trigger for accessing their own knowledge and experience and therefore do not work with the provided information. As a consequence, the DSS fails as a tool: decisions are made without consideration of the provided information and are based solely on personal experiences and preferences. Consequently, there is a high risk that participants will be frustrated about the DSS or even ignore the provided information, because they cannot find common sense and reasons for common decision making.

5.5. Conclusions

This study investigated user behaviors and cognitive processes while applying ES information integrated in a DSS. These results are information and user-group sensitive and do not necessarily support general statements about demands on ES information. Further, the results do not describe ES specific requirements. Instead, the study outlined the complexity of providing DSS and ES or environmental information as well as the relevance of user demands. The results of the ET approach show that the use of ES information by representation type depends on the intention of use. Further, cognitive processes varied among the participants. These results indicate the importance of multiple types of representation and the option of combining them to provide ES information.

Making general recommendations on how ES or environmental information should be represented and communicated is difficult. The information framework seems to be heavily context and user sensitive. In particular, the user behaviors and demands could vary among information content, region and reason or purpose why information is provided. This makes it challenging to meet all user demands. However, a good approach for covering such unpredictable user behaviors and demands is to provide a large set of types of representation that vary in visualization style, display type and scale. This allows users to filter and select the information they deem most supportive and relevant.

Furthermore, results show how the representation type characteristics of ES information influence the behaviors of users. Especially, detail and scale between applied information and reasoning is correlating, which describes the power of information provision and therefore the key for its operationalization. This could mean also in case of ES concept operationalization, tiered approaches are required as well as a variety of representing ES data to provide supportive information at different scales and for heterogeneous user groups.

Acknowledgments

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6. Chapter VI: Tool conception

LANDSCAPEization: A toolkit for visualizing landscapes in ecosystem services assessments

Abstract

The operationalization of the ecosystem services (ES) concept is often impaired by the lack of detailed information needed by experts for local decision making. While the concept with its broad categorization ranging from supporting, producing, regulating, and cultural services allows various environmental aspects at various scales to be addressed, the current information provided to decision makers is often based on ES supply maps, missing information related to cultural ecosystem services (CES), the demand for ES, the state of the ecosystems, or costs for various management strategies, to name a few. In this paper, we present the LANDSCAPEization toolkit, which allows the visualization of and reporting on ES- and non-ES-related information in real-time over spatial scales. Embedded in a decision support system, the provided information supports the communication of land use changes and their impacts on ES. By allowing 3D visualizations of land use patterns in real-time, the toolkit allows the communication of changes in the landscape and thus supports trade-off assessments between cultural ecosystem services and other ES. Additionally, besides interactive functionalities for accessing ES- and non-ES-related information, the LANDSCAPEization toolkit also allows a participatory mapping and rating functionality for cultural ecosystem services and thus offers an innovative approach to support integral ES-informed decision making across all ES categories.

6.1. Introduction

Environmental communication plays a key role in transferring knowledge about environmental issues to the public. According to Jurin et al. (2010), environmental communication is defined as the "systematic generation and exchange of humans' messages in, from, for, and about the world around us and our interactions with it." This definition highlights the significance of knowledge transfer to practice, which is a key factor in raising awareness of environmental issues (e.g., Cantrill, 1993). As such, environmental communication is thus well suited to support the operationalization of concepts or novel developed approaches (Cox, 2016;

Jurin et al., 2010), such as the ecosystem services (ES) concept.

The concept of ES describes the benefits people obtain from ecosystems and is suitable for communicating the dependence of human well-being on ecosystems (MEA, 2005; Schwilch et al., 2016). The categorical approach of the ES concept to supporting, producing, regulating, and cultural services allows many environmental fields and stakeholders' interests to be addressed. However, while there is growing interest in ES-based policies, there is still a lack of intersectoral efforts (Wamsler et al., 2016) and suitable ES decision-support tools for a sound operational integration into policy (Kettunen and ten Brink, 2015; Kettunen et al., 2014). Furthermore, the provided ES information is often not comprehensive enough to support local decision making: non ES-related information, such as e.g., indicators about the vitality of a forest or the costs of an intervention, linked to the ES to be fostered are missing and thus unavailable for decision makers attempting to define implementable management plans (e.g., Rammer and Seidl, 2015; Verkerk et al., 2015). Such approaches to linking additional information with ES information are only rarely provided to decision makers (e.g., Wissen Hayek et al., 2016) but would allow stakeholders not only to better understand and assess the legitimacy of the communicated environmental issues but also to reason based on their own arguments in an interdisciplinary exchange.

Fostering the consideration of cultural ecosystem services (CES), besides provisioning, regulating, and supporting services, is an important benefit of the ES concept (Riechers et al., 2014). CES describe a variety of place-related settings and the "social-ecological and/or non-material benefits people obtain from a contact with ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience" (La Rosa et al., 2016). However, there is still a lack of conceptual clarity and ambiguity in the use of CES categories (see La Rosa et al., 2016). The complex motives of CES, where socially patterned and symbolically powerful experiences of places and landscapes are involved (Nahuelhual et al., 2015; Winthrop, 2014), make their use in ES assessments difficult. Existing and frequently applied CES mapping approaches (e.g., inVEST, www.naturalcapitalproject.org/invest) often ignore the local and individual as well as cultural values of society, while simply using coarse-scaled GIS datasets (e.g., historic buildings). Furthermore, modelling approaches that attempt to consider CES in a more complex and comprehensive manner by consideration of, for example, social behaviors (e.g., accessibility) linked to ecological factors (e.g., biodiversity) are mostly limited to particular CES (e.g., recreation quality, landscape scenic quality; c.f., He et al., 2016; La Rosa et al., 2016). But communicating CES in a way that would enable users and stakeholders to voice their opinion is important for assessing ongoing landscape changes in terms of their social-cultural, social-ecological, and aesthetic aspects. Stakeholder involvement, particularly in participatory mapping (crowd sourcing), has been shown to allow the assessment, mapping, and quantification of the social values of CES (Brown et al., 2011, Sherrouse et al., 2011). However, the approaches in these studies have been limited to asking stakeholders to rate maps showing locations where CES are provided, ignoring the social construction of environmental experience (e.g., Minaei, 2014).

While policy calls for better ES maps to support decision making (e.g., Action 5 of the EU Biodiversity Strategy to 2020; EC, 2011), political decisions are more often driven by emotion, stories, and ethical values than by "cold, hard numbers" (e.g., Anderson, 2014; Menzel, 2013). Several authors have shown how landscape visualizations, in particular, can raise awareness (Grêt-Regamey et al., 2013; Klein et al., 2015; Paar, 2006; Wissen Hayek, 2012; Sheppard et al., 2005). Although many GIS-based and interactive landscape visualization tools are available, most do not support an integration of highly detailed vegetation objects. Biodiversity is, however, known to influence the assessment of the aesthetic attractiveness of landscapes and thus potentially influences choices or decision making (Brunner et al., 2016; Junge et al., 2011; Lindemann-Matthies et al., 2010; Lindemann-Matthies and Marty, 2013). Furthermore, highly detailed visualizations can provide a sense-of-place in the virtual landscape, also making other CES identifiable. Embedded in a decision support system (DSS), such visualizations can support users in investigating the effects of land use change on landscape attributes and related ES (Grêt-Regamey et al., 2013; Klein et al., 2013; Wissen Hayek et al., 2016). The interactive functionalities can allow users to create scenarios to analyze and understand interdependencies in environmental issues in terms of their natural complexity and the effects of policy instruments (c.f., Celio et al., 2015; Grêt-Regamey et al., 2013) and finally also foster action (e.g., Nassauer, 2012; Wissen Hayek and Grêt-Regamey, 2012). Such an interactive "geodesign" approach further supports experimentation with different alternative landscapes, enabling the design and communication process to incorporate uncertainties of future developments (Nassauer, 2012).

In the following, we present a toolkit that allows the generation of virtual landscapes and the reporting of ES- and non-ES-related information for ES assessments over spatial scales in real-time. Integrated in a DSS, the module-based toolkit was designed for experts and laymen for communication of land use changes with their impacts on ES. Besides interactive functionalities for accessing ES information at various spatial scales, the LANDSCAPEization toolkit also allows a participatory mapping and rating functionality for CES and therefore offers an innovative approach to supporting integral ES-informed decision making across all ES categories.

6.2. Methods

6.2.1. Conceptual framework

The LANDSCAPEization tool provides different modules that are linked together to allow the visualization of landscapes and the reporting of the indicators describing

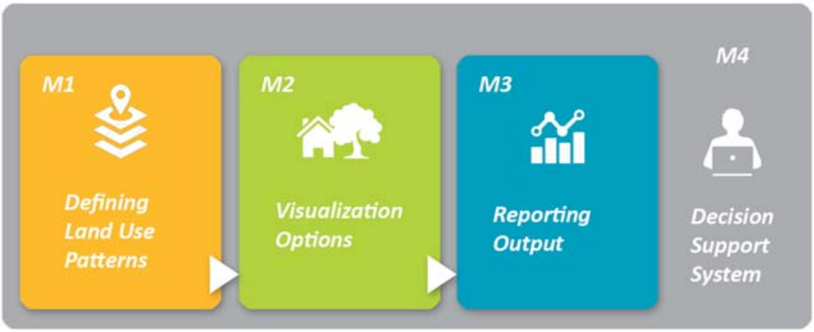

Figure 13 - Conceptual framework and links between different modules (M) for land use pattern visualization and reporting output provided by a decision support system front-end.

them (including ES). Figure 13 provides an overview of the four modules (M) integrated within graphical user interfaces, aimed at defining and processing landscape visualizations with indicators (M1–M3) and at providing access to this processed information, including mapping and rating functionalities (M4). The modules include the following functions: M1 allows the user *to define land uses* by linking spatial data with the configuration options of the other modules, M2 enables settings to *visualize land uses*, M3 allows the user *to configure reporting*, and M4 defines *the front-end DSS* for accessing the processed information and interactive functionalities.

Anchored in the definition by the European Landscape Convention, landscapes are "areas, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (European Landscape Convention, Council of Europe, 2000) – the LANDSCAPEization tool is based on land use patterns and their landscape elements, as these are the expressions of the landscape. While M1 enables the importing of spatial datasets such as land use maps, which are themselves constituted by various landscape elements described by their spatial distribution (e.g., the density of trees within a forest patch; Table 7), M2 allows users to define the land use types in terms of the various landscape elements and the characteristics they want to display in 2D, 2.5D, or 3D. In M3, various indicators can be linked to the landscape elements or land use types to provide additional information (e.g., ES indicators) to the landscape's visualizations. For example, a tree type of a specific age can be linked to ES information such as timber production or CO_2 storage (see Table 7). Such attributes of the landscape elements can be linked to various indicators, which can then be reported according to each land use type. This information and visualizations are the base for the DSS front-end of M4. The DSS front-end

Table 7 - Example of two land use types with their landscape elements and characteristics and indicator values, based on Broward (2016) and Rast (2016).

Land use type	Landscape elements	Element characteristic	Deployed 3D object	3D object preview (example)	Landscape element proportion within land use type	Indicator values (examples)
Mixed forest type A	beech tree	15-20 years	beech20y_1.dae beech20y_2.dae beech15y_1.dae beech15y_2.dae		42%	solid cubic meter: 0.47 CO_2 seq./year: 13 kg green mass: 84 kg
	oak tree	30-35 years	oak25y_1.dae oak25y_2.dae oak15y_1.dae oak15y_2.dae		10%	solid cubic meter: 1.41 CO_2 seq./year: 30 kg green mass: 189 kg
	spruce tree	15-20 years	spruce20y_1.dae spruce20y_2.dae spruce15y_1.dae spruce15y_2.dae		48%	solid cubic meter: 2.41 CO_2 seq./year: 37 kg green mass: 237 kg
Settlement zone type A	single family house	2 floors	building1_1.dae building1_2.dae		75%	floor area ratio: 1 persons: max. 4 soil sealing: 375m²
	apartment house	5 floors	building2_1.dae building2_2.dae		25%	floor area ratio: 2 persons: max. 18 soil sealing: 875m²

includes various tool functionalities for analyzing, filtering, mapping, and rating areas or landscape elements in addition to scenario-controlling functions. By allowing users to map and rate areas according to their CES values as a Participation Geographic Information Systems (PGIS) function, the local significance for CES and various interests can be considered. Further, by modifying the input land use or landscape elements datasets, users are able to run scenarios to understand potential impacts of a land use change on various ES as well as on the scenic beauty. In the following, more technical details on each module are provided.

6.2.2. Technical specifications

6.2.2.1. Defining land use patterns (M1)

Land use and the spatial distribution defined in land use maps can be uploaded into the DSS in the form of spatial datasets. Subsequent settings available in the other modules (M2–M3) can then be linked to these datasets. Uploaded data in a GIS vector shape format (*.shp) are inserted into a PostgreSQL database using the Geospatial Data Abstraction Library (GDAL) (www.gdal.org). Then, the graphical user interface (GUI) will prompt the user to define the land use by selecting a desired attribute name and the various attribute values of the spatial dataset the user is interested in displaying.

6.2.2.2. Visualization options (M2)

Users are able to set a visualization type (2D, 2.5D, 3D; Figure 14; Figure 15) based on the attribute and attribute value selections made in M1 and to select between different options to represent land use types. The visualization settings, which depend on the visualization type, contain various options to colorize land use shapes (2D), to extrude and colorize land use shapes (2.5D), or to represent land use by landscape elements, that is, 3D objects in the COLLADA file format (*.dae) (3D). After the visualization options for specific land use types have been set, the module will automatically generate three different keyhole markup language (KML) files, one for each visualization type. These files include all colorization data (2d.kml), all texturing settings (25d.kml), and all linked and allocated 3D objects (3d.kml). The files can then be rendered on Google Earth API-based environments (https://developers.google.com/earth) in real-time.

For the 2D visualization type, a color value needs to be defined for each land use type to colorize shape areas. There is also an option to link an image file (.png) to texture the shape and to extrude surfaces by 2.5D visualization type. In addition, the 2.5D visualization type requests the definition of a height extrusion of the shape areas (e.g., by an attribute value of a linked spatial dataset or by a fixed defined height value). This option allows the user to extrude the land use types' shape areas, where the value (in meters) has been defined or linked from an attribute of the dataset. On one hand, the function can be used to display shape areas in a 3D view (i.e., as an abstract 3D visualization by using attribute values of the spatial dataset to visualize, for example, monetary values as a geo-statistical representation). On the other hand, it can be used for a simplified visualization of a land use type considering the appearance of the landscape instead of using 3D objects, for example, average tree height as the height value for an extruded forest area (compare Figure 14).

For the 3D visualization type, 3D object layers represent landscape elements. Each 3D layer also requires a parameterization to define its 3D objects' distribution in space (i.e., proportion, density, overlapping, minimum distance, orientation, randomness) within a specified land use. The object distribution can be regular, random, or pattern defined. The latter can be defined by linking an image file (*.png) as a function of a density map to allocate 3D objects by grey-scale values of image data (white = 0% of defined density value [numbers/hectare], black = 100% of defined density value).

6.2.2.3. Reporting (M3)

Users are allowed to define specific indicator values based on land use types by area and/or landscape elements (Figure

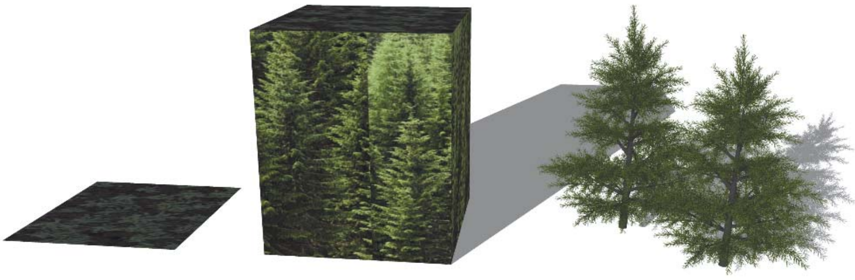

Figure 14 - Available visualization types (M1): 2D visualization with colorization or image texturing option; 2.5D visualization by extrusion, colorization, or image texturing option; and 3D visualization by linking 3D objects (COLLADA files) and the parameterization of landscape elements by land use type characteristics (e.g., proportion, density).

16). Defined indicator values per landscape element are then summed up depending on the amount of allocated landscape elements. For each polygon feature of linked spatial datasets, the defined indicator values are automatically saved in a new attribute column. To access these indicator values by land use type and landscape elements, users can configure a personalized reporting output. This output is visualized in different chart types using the D3.js library (www.d3js.org).

6.2.2.4. DSS (M4)

The front-end for accessing the processed landscape visualizations and the indicators' information (M1–M3) is designed as a DSS (Figure 17). The GUI of the DSS contains i) a Google Earth API frame that renders the landscape visualizations (M2) based on linked land use datasets (M1), ii) a scenario controlling the menu for choosing between different land use types and therefore different linked land use datasets (M1), iii) a reporting frame that presents defined indicators' values for the selected dataset (M3), and iv) a toolbar to access various functionalities for navigation (e.g., changing to pedestrian view) and to support more intuitive analyzing, filtering, evaluating, mapping, and rating of sites with their specific characteristics.

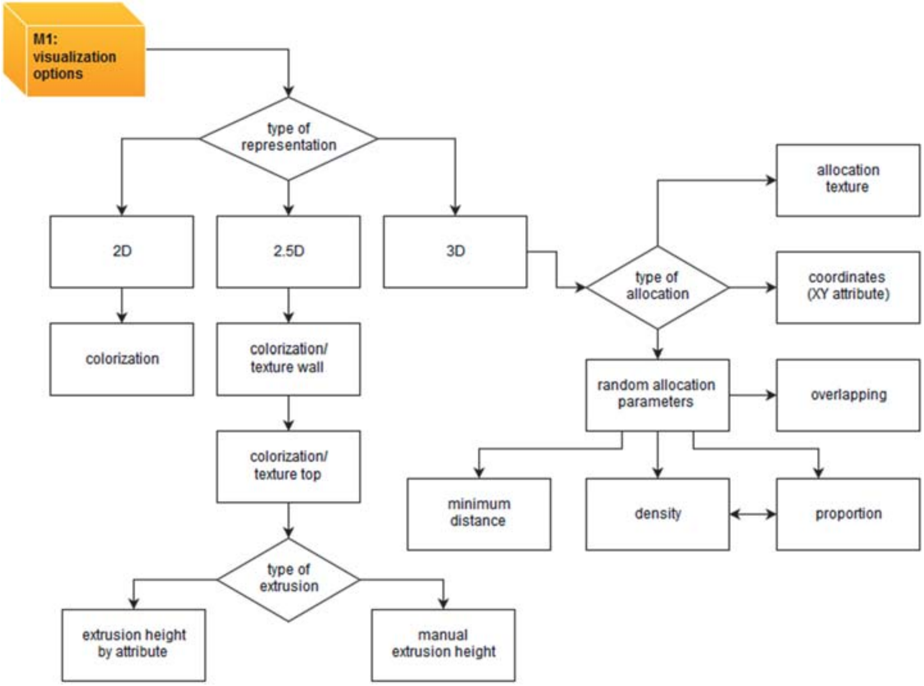

Figure 15 - Technical functions of M2 for visualization options.

6.2.2.5. Point cloud data for realistic 3D landscape visualization

In addition to the above-mentioned functionalities, the provided toolkit allows users to import LiDAR (light detection and ranging) 3D point cloud datasets to provide highly detailed landscape visualizations (c.f., Kreylos et al., 2008; Kuder and Žalik, 2011). This type of landscape visualization enables a real-world level of detail in the virtual globe of Google Earth API. A database approach has been developed for the web-rendering of such large datasets of LiDAR point clouds using the actual viewport parameters (camera position and height, view angles) to render only relevant point cloud data within Google's API. Depending on the distance to the camera position and the viewport, the script renders relevant points iteratively by gaining point cloud density. With this iterative approach, objects are rendered immediately in a fuzzy quality, and the level of detail increases until there is a change in the setting of the viewport parameters.

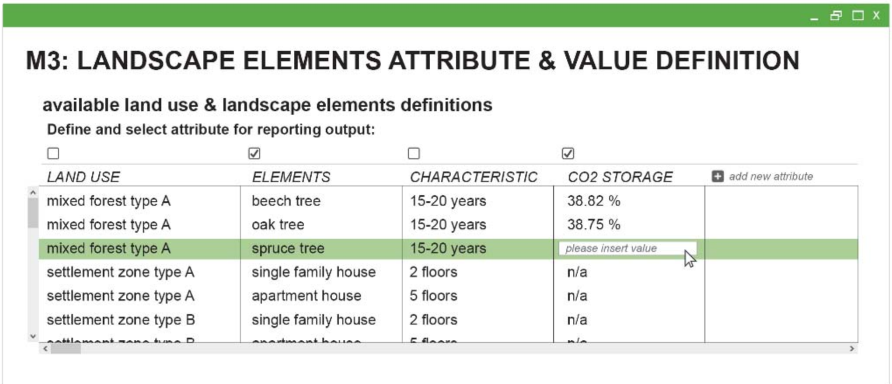

Figure 16 - GUI of M3 for defining attribute values by landscape elements. CO2 storage values of trees were chosen for exemplary purposes, based on Higuera and Martínez (2006).

6.3. Results

The front-end of the web-based DSS (M4) is shown in Figure 17. The DSS provides information about land use patterns (M1), visualized (M2) and combined with a reporting of indicator values related to the land use types and the landscape elements (M3). Hence, users can feel the real-world "sense-of-place" of the areas by looking at a realistic visualization with a high level of realism, enhancing their assessment of scenic beauty and potentially other CES (Figure 18).

Figure 17 illustrates an example of a land use change scenario in a settlement area. The land use change takes place on an empty lot that is currently used as an agricultural area. It changes into a high-density building zone, represented by a mix of housing types. In this example, the allocation of the buildings within the lot was defined by allocation parameters, including the size of the lot, and the theoretical maximum number of buildings, which is based on a minimum distance space between buildings. The number and type of allocated landscape elements (i.e., in this example, building types) is protocolled. This protocolled information is used to calculate the various indicator values reported in the DSS. The interactive feature with the automatic update of information about the changes in land use, landscape elements, and their indicators enables users to interactively identify the environmental impacts of such changes. Through the interactive navigation (freely definable points of view, filtering/selection functions, and scenario selection), users can study their places of interest. In doing so, they can assess how land use changes affect the scenic beauty at a given location (Figure 17).

For technical details please see Apenidx III.

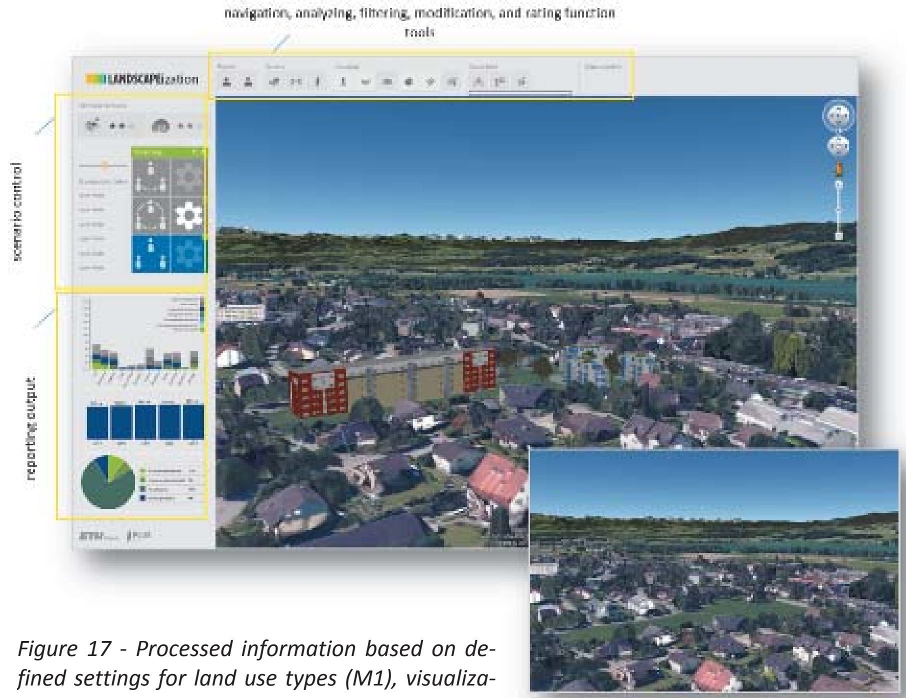

Figure 17 - Processed information based on defined settings for land use types (M1), visualization options of land use types and landscape elements (M2), and indicator reporting (M3), embedded in a front-end DSS (M4).

Since the toolkit allows the estimation of ES based on land use and/or landscape elements, a detailed ES mapping approach can be provided (Figure 19). By integrating PGIS functions in the DSS (e.g., crowd sourcing functionalities), users can map important sites providing, for example, CES or rate specific sites or landscape elements that provide cultural value.

6.4. Discussion

The developed LANDSCAPEization toolkit allows the generation of highly realistic virtual landscapes linked to ES information. Impacts on ES of various land use change scenarios can be visualized and communicated rapidly, thus supporting a qualified selection of land management strategies (Erb, 2015). The real-time generated, highly realistic visualizations based on land use datasets can effectively support the evaluation of CES (Kuder and Žalik, 2011), granting the user a realistic landscape perception, as recommended by Bergen et al. (1995). Furthermore, the user-centered and customizable DSS framework allows heterogeneous user groups to customize the ES information they are interested in – a key feature for

Figure 18 - Spatial-referenced LiDAR data of a group of trees visualized as a colorized 3D point cloud (left) embedded in Google Earth API's virtual globe (middle) enables a realistic landscape view (right) and therefore an enhanced assessment of the landscape's aesthetics, sense-of-place, and potentially other CES.

operationalizing the ES concept (Klein et al., 2015).

The interactive functionalities provided by the LANDSCAPEization toolkit open new possibilities in mapping and assessing CES by addressing some of the challenges identified in CES assessments (Brown and Fagerholm, 2015; Crossman et al., 2013; Egoh et al., 2012; Martínez-Harms and Balvanera, 2012) – notably, the importance of considering individuals' perceptions, behaviors, and appreciations of CES in various landscapes (Klein et al., 2016; Tress et al., 2001; Wu, 2013). The area rating function (PGIS), for example, allows users to value areas with regard to their provision of cultural values, which can support users in participative planning approaches to mapping CES values (Brown and Fagerholm, 2015; Daniel, 2001; Voinov et al., 2016). This provides the public with access to a spatial valuation tool supporting individual valuation and respecting individuals' landscape perceptions and therefore cultural values at local scales (Appleton and Lovett, 2003; Daniel, 2001). Furthermore, the realism of the visualized landscapes enables tackling the quality of the CES, which otherwise often depends on single or rough-scaled GIS datasets, thus not reflecting local characteristics (Hussain and Ujang, 2014; Mutlu Danaci, 2015; Penića et al., 2015). However, the CES mapping and rating functionalities embedded in the LANDSCAPEization toolkit do not yet contain any definitions of the various CES and related indicators, which would support comparisons between studies (La Rosa et al., 2016).

By embedding the free and open access Google Earth API into the DSS framework, the visualizations of the LANDSCAPEization toolkit gain credibility and representativeness (Sheppard and Cizek's; 2009). Furthermore, Google Earth provides up-to-date information, while the toolkit allows additional inputs of custom data, for example, by Web Mapping/Feature Services (WMS/WFS). While maps typically provide generalized and filtered information, aerial images show detailed and "raw" information. In particular, in participatory planning workshops, users often ask for public access to information that is

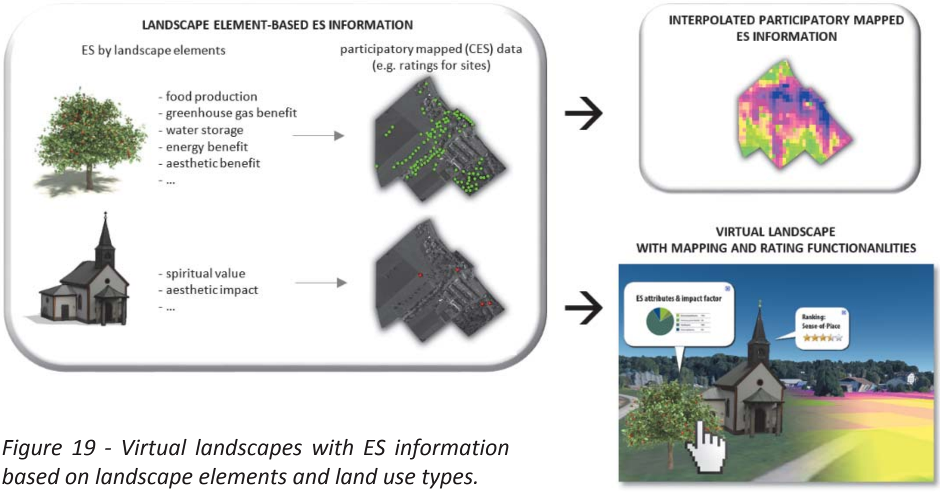

Figure 19 - Virtual landscapes with ES information based on landscape elements and land use types.

available from web-based technologies, such as in the presented tool, thus allowing easy and broad access. However, there are also limitations associated with virtual globes such as Google Earth, especially concerning the use of detailed data depending on the data volume as well as bandwidth, rendering, and computing time limitations. In addition, the quality of the LANDSCAPEization toolkit is highly dependent on external input: on one hand, the highly realistic landscape visualizations depend on the availability of 3D virtual objects, available in various databases such as the SketchUp 3D warehouse (http://3dwarehouse.sketchup.com). On the other hand, the indicators depend on various data related to the landscape elements, such as the plant trait database of TRY (www.try-db.org), which comprises information about plant-specific chemistry and biological facts with more than five million trait entries for 100,000 plant species, or economic values of ES (e.g., www.teebweb.org), which can support economic discussions in terms of land management (De Groot et al., 2012; Mc Vittie and Hussain, 2013).

The presented toolkit allows improved environmental communication in two ways. On one hand, the provided reporting functionalities with enhanced possibilities to include non-ES-related information in combination with ES-related information and landscape visualizations enable a deeper understanding of environmental issues in addition to ES information. On the other hand, the embedded PGIS functionality enables a direct feedback channel for the audience/users. However, options to provide more detailed (background) information about, for example, land use scenarios, as well as feedback options to comment on such provided information, are not yet embedded in the LANDSCAPEization toolkit. Such feedback features could be particularly necessary to enable more extensive communication and to define in a transdisciplinary process, for example, land management strategies.

Through the integration of both ES- and non-ES-related information, the LANDSCAPEization tool supports the communication between users with different disciplinary backgrounds or various sectoral policies (Kettunen et al., 2014; Kettunen and ten Brink, 2015). This could contribute to a better integration of ES-related aspects into sectoral policies while using common ES indicators as an information base for finding common strategies across sectors and institutions (Kettunen and ten Brink, 2015). While the toolkit's focus lies on information provision for decision support at local scales, its use at various coarser scales is supported through the customizable reporting options. Although the LANDSCAPEization tool provides a technical framework for such a transdisciplinary approach to ES information provision, the tool still requires a great deal of input from the user on elements from land use types to the landscape elements and the relationships by which to quantify and/or value ES.

6.5. Conclusion

The presented LANDSCAPEization tool, with its module-framework and web-based DSS front-end, encompasses features to inform users about land use-related ES. The communication of CES is supported by the generation of landscape visualizations in real-time. Furthermore, the developed technical interfaces allow the individual linking of ES and other indicators to land use or landscape elements to support transparency in information provision and communication. With its participatory functionalities, the DSS also supports participative approaches to CES mapping and valuation. This facilitates integral assessments and trade-off-making across all ES categories to support sustainable development.

Acknowledgments

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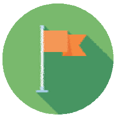

7. Chapter VII: Synthesis

7.1. Main conclusion

The goal of this Ph.D. project was to investigate visual communication approaches for ES information for implementation in a DSS in order to support ES-based decision making, including the consideration of CES. To cope with unknown user demands, the thesis used requirements engineering approaches, including usability testing methods, for identification of the required features of visualizations and DSSs. The identified features were implemented in a novel toolkit called "LANDSCAPEization." The objectives were approached via three first-authored papers completed during this Ph.D. project. By referring to the initial research questions and hypotheses (*Section 1.3.1*), the main conclusions can be summarized as follows:

- User demands for ES information strongly depend on how they intend to apply the information. Furthermore, the setting of the application and individuals' preferences, skills, expertise, or interests can influence these demands (*Chapter IV*). Out of the highly heterogeneous demands of users, five components describing the representation type, depending on the application and intended use of the ES information, were identified: (1) 3D landscape visualizations are generally requested by users for analyzing and exploring ES-related information, which however indicates their interest also in considering CES, as for example landscape aesthetics can be intuitively identified by such representation types. (2) Texts or text abstracts about ES information are requested to support general communication as well as to support users in discussions, as this kind of representation type allows for easy access to concrete and (pre-)formulated ES information and facts. (3) Thematic 2D map representations are requested by users for scenario development in public applications, as these representation types can provide a quick and entire overview of regions. (4) Abstract 3D landscape visualizations facilitate estimations in group applications, as they could provide thematic ES information in a realistic field of view to simultaneously allow consideration of CES. (5) Charts and tables; in combination with thematic 2D map representations are requested to help users analyze spatial ES information, as such a combination allows detailed spatial analysis for investigating only specific places or areas of interests by maps and also quick and easy access to the summarized information via charts or tables.

- The behaviors and demands of DSS users significantly differ depending on their connection to the case study area. Therefore, ES information users' preferences vary, which consequently influences their cognitive processes, reasoning, and decision making (*Chapter V*).

- In order to communicate ES information based on the results of the demand analysis and usability testing, the toolkit "LANDSCAPEization" was developed. It provides a generic landscape visualization feature and allows participatory approach for the consideration of CES, and enables an interactive trade-off assessment of all ES categories (*Chapter VI*).

Firstly, the subsequent sections present the important findings of this thesis with regard to the initial research questions and emphasize on the impact of the results on practical implementation. Secondly, they highlight how the results of this work were validated using a participative approach. Finally, an insight into potential future research is provided, along with final conclusions.

7.2. Implementation of the findings related to ES information provision in a DSS

Providing ES information in a suitable form is important for targeted communication and bringing the ES concept into practice (e.g., Grêt-Regamey et al., 2014; Grêt-Regamey et al., 2012). DSS-implemented ES information needs to be readable and understandable in order to support users in its application (e.g., Klein et al., 2015; Wissen Hayek et al., 2016). To identify and develop suitable ways of communicating ES information for decision support, three key research questions (see *Section 1.3.1*) were addressed in this thesis:

1. What are the requirements and demands for ES information representation in order to support decision making?

Since the European Commission called upon their Member States to map ES and support the implementation of ES information in policy and decision-making processes (MESEU, 2014; European Commission, 2013), research projects such as the EU's 7th framework, OPERAs and the OpenNESS project have been launched to improve the operationalization of the ES concept and, therefore, bridge the gap between science, policy, and practice (OPERAs, 2016; OpenNESS, 2016). There is no doubt that DSS can support the implementation of ES information in policy and decision making, but there is no consensus about how ES information should be provided to efficiently support DSS's user applications.

Chapter IV shows how a demand analysis can be defined to identify user requirements for DSS-embedded ES information. The results show that there are very heterogeneous demands for ES information in the ES community as a whole. The presented methodological framework can be potentially applied to project-specific stakeholders or DSS users to provide suitable ES information and tools. Furthermore, the results emphasize the need for various representation types, which support multiple user purposes for applying the ES information. These specific intentions of users are key for providing suitable information considering the settings and functions in applications, and, therefore, in creating a useful DSS.

The demand analysis results show, however, that five components, which differ according to their representation types, are requested depending on the context of the application and the intended use of the ES information: (1) 3D landscape visualizations for analyzing and exploring ES-related information, (2) texts and text abstracts for communication and discussion support, (3) thematic 2D map representations to support scenario development in public applications, (4) abstract 3D landscape visualizations for estimations in group applications, and (5) charts and tables in combination with thematic 2D map representations to support analyses. These results were contradictory, in some areas, to other studies (Hauck et al., 2013) or even statements of the EU Biodiversity Strategy (European Commission, 2013), as they recommend maps for general communication of ES information. In contrast to these recommendations, the demand analysis results identified text and text abstracts as a preferred representation type for communication and discussion support. Further, maps are preferred for supporting scenario development in public, in combination with charts and tables to support analyses. There is an overflow of maps for ES information in ES community as a result of the lack of processing and therefore conversion of modeled or mapped ES data into other representation types and therefore potentially more tailored ES information (e.g., other representation types) based on user demands. Nevertheless, the purpose and the kind of situation where potential users want to apply ES information will never be entirely foreseeable. This means that providing only a single representation type limits the potential use of ES information in practice. Therefore, information providers and tool developers should provide comprehensive visualization options so that ES data can be presented as a combination of multiple representation types to allow its broad application for various intentions and situations. These communication options are also emphasized by the demand analysis results, as thematic 2D maps were only requested by users in combination with charts or tables, as the latter potentially provides already more aggregated or filtered ES information. Finally, the provision of ES information should not be restricted by the lack of final preparations to provide useful information with a set of different representation types.

A demand analysis can include a complete set of options. Thus, representation types, display scales for ES information, and DSS functionalities can be requested which, in practice, potentially ignore existing technical limitations or practicability. Furthermore, the results were generated by a theoretical approach in which participants rated their preferences and demands without hands-on applications or specific and practical project needs. Thus, the identified user requirements provided by the demand analysis pointed to the need for a second research question:

2. How do theoretical user demands for ES information match with the practical application of a DSS, and is there a difference in user behaviors between DSS applications, depending on their connection to the case study area, that potentially influences cognitive processing, reasoning and therefore decision making?

This thesis has shown that in the practical application of DSS-implemented ES information, user preferences for representation types and their characteristics—e.g., display scale, and interactivity—all depend on how they intend to apply the information (*Chapter V*). In addition, this behavior varied between users with and without connection to the case study area. These preferences and the filtering effects of ES information consequently influenced cognitive processes, reasoning, and, therefore, the decision-making process of users. The findings emphasized that it is important to provide (within a DSS) diverse representation types for ES information to serve heterogeneous user groups. In contrast, the knowledge in place in the case study affected ES information users to act alternatively through their cognitive processes. This creates a dichotomy between emotional and objective landscape perceptions and reasoning by users (e.g., Winkler and Nicholas, 2016; Scholte et al., 2015; Soini et al., 2012). For example, users with a connection to the case study area were more often swayed by the aesthetic characteristics of the landscape, and therefore tried to identify landscape changes via the provided scenario information to infer the effects on the complete case study region. Based on the results presented here, improved knowledge and understanding in the decision-making process related to representation types will support optimized and user-tailored ES information provision.

Furthermore, the theoretical demands (first key research question) were basically confirmed or re-identified by the second key research question (Paper II), as in the eye-tracking study, users preferred representation types which strongly depended on the intended use of ES information. The resulting five components of the demand analysis (Paper I) were identified again based on the behaviors of users applying the DSS. ES information provided by chart representations was mainly used in combination with map information. However, the provided text abstract, including scenario information, was also neglected by the majority of the users. Further, for spatial analysis, users mostly used the map representation, often in combination with charts. Maps were also often used for scenario development. Unfortunately, the eye-tracking study did not provide clarity about the theoretical demands with regard to the use of 3D landscape visualizations. The results of the demand analysis show that 3D landscape visualizations are requested by users for analyzing and exploring ES-related information. However, the results of the eye-tracking study do not confirm this request integral. Thus, it can be assumed that this request potentially indicates users' interest in CES while analyzing and exploring ES-related information by other representation types: 3D landscape visualizations are used for reading out CES information simultaneously. While the DSS integrated static 3D landscape visualizations that allowed users to explore and analyze the preset field of view, the ES information provided by this representation type was restricted to a local site. However, 3D landscape visualizations were preferred consequently to text information. Especially when the DSS was used for a decision-making process that also addressed the aesthetic aspects, the use was disproportionally high. The eye-tracking data as well user reasoning measured by cognitive probing confirmed that there is a demand for various representation types of ES information. None of the users had used only a single representation type for a specific purpose; they all combined various representation types for retrieving ES information on various scales and details. The results show that applying and using ES information efficiently requires a set of various representation types.

3. How can knowledge about user demands for ES information be implemented in a novel toolkit for communicating all categories of ES information?

Previous studies have shown that CES are often neglected or reduced to a single service in ES assessments (e.g., La Rosa et al., 2016; Wissen Hayek et al., 2016). This leads to an unbalanced trade-off between ES and thus biased decision making. This is often the result of missing data on CES values, which need to be generated in normative quantification processes (Winthrop, 2014; La Rosa et al., 2016). To address this challenge, the web-based toolkit "LANDSCAPEization" provides a generic workflow for ES information-based representations and landscape visualizations. The ES information-based approach enables users to link ES information and other indicator values (e.g., CO_2 sequestration or timber production by solid cubic meter values) to landscape elements (e.g., tree species) or land use types to model and evaluate ES trade-offs in consideration of the CES e.g., scenic quality and sense of place. Through the use of landscape visualizations combined with detailed ES information reporting, which is based on land use patterns constituted by land use types with their specific landscape elements, a comprehensive trade-off assessment between all ES categories is possible. In addition, to enable CES assessment via a high level of realism, a script was developed to integrate LiDAR point cloud data for visualizing the current site's characteristics in high detail and in terms of their actual "sense of place." Furthermore, considering missing CES data and their complex acquisition, we developed a DSS functionality that enables participative mapping and evaluation of sites based on their individual cultural values and meanings. With this functionality, CES can be integrated into trade-off assessments and thus decision-making strategies. The toolkit thus allows planners to create easy and rapid web-based landscape visualizations to communicate future landscapes and their impact on ES through land use management by linking GIS-based scenario data sets.

In this thesis, we do not challenge the importance of ES information provision, but identify the potential inefficiency of using inappropriate representation types, DSS components, and technologies for communicating landscape qualities. The thesis also provides new insight into the behavior of users of ES information in decision-making processes. Providing additional supportive information could avoid illegitimate or disproportionate user reasoning and consequently support better decision making. An increase in information could influence the evaluation process and could therefore influence users' cognitive loops during the decision-making process (Jelokhani-Niaraki and Malczewsky, 2014).

Finally, established decision-making strategy theories by Vessey (1991), Vessey and Galleta (1991), or Sugumaran and de Groote (2011) are extended by this thesis's findings: Depending on the additional constraints (e.g., time pressure to accomplish a task/making a decision), DSS users try to find a balance between accuracy-optimized and effort-optimized decision making. Their decision-making behavior depends on their expertise, experience, difficulty of the task, or their knowledge of where to find relevant information in DSS. This finding related to experience-based influence can be further potentially linked with the description-experience-gap of Kahnemann's prospect theory (Kahnemann and Tversky, 1979). In fact, the description-experience-gap of the prospect theory can explain differences in probability weighting based on experience versus dependency only to information whereby users with experience underweight a probability and description-dependent users overweight a probability (Hertwig and Erev, 2009). However, in contrast to the approach in this thesis (Paper II), the prospect theory is based on a probability framework which is different from the DSS approach of the usability study: users were not able to identify any probability information about scenarios or their constraints, so they were not able to estimate any likelihood and unlikelihood from the provided information. Further, it is unclear how this factor plays a key role in DSS application as the user's belief in such a system is a prerequisite to profiting from the tool's actual function. Moreover, the cognitive interview results indicate behaviors that are contrary to the description-experience-gap theory (Hertwig and Erev, 2009): users with knowledge in place consequently reasoned and therefore potentially overweighed their experience with regard to specific facts. The results further show that users tend to develop alternative decision-making strategies if the provided information does not match their cognitive notion; sometimes, they do not want or were not able to make decisions due to lack of information, which led to inconclusiveness. Local expertise, for example, led to alternative decision making: Users from the case study area used the information provided only as a trigger for reasoning, while they mostly based their reasoning on information that was not provided.

7.3. Advanced findings

Transdisciplinary usability and the benefits of participative planning

In order to validate the practicability of the findings of this Ph.D. thesis, a DSS prototype (Figure 20) of the developed toolkit was applied in a participative planning workshop with local stakeholders (Figure 21). The goal of this workshop was to assess various scenarios and to determine their acceptance of future landscape developments with respect to pressure from settlement zone changes, depending on policy instruments and their effects on the ES in the case study region. Altogether,

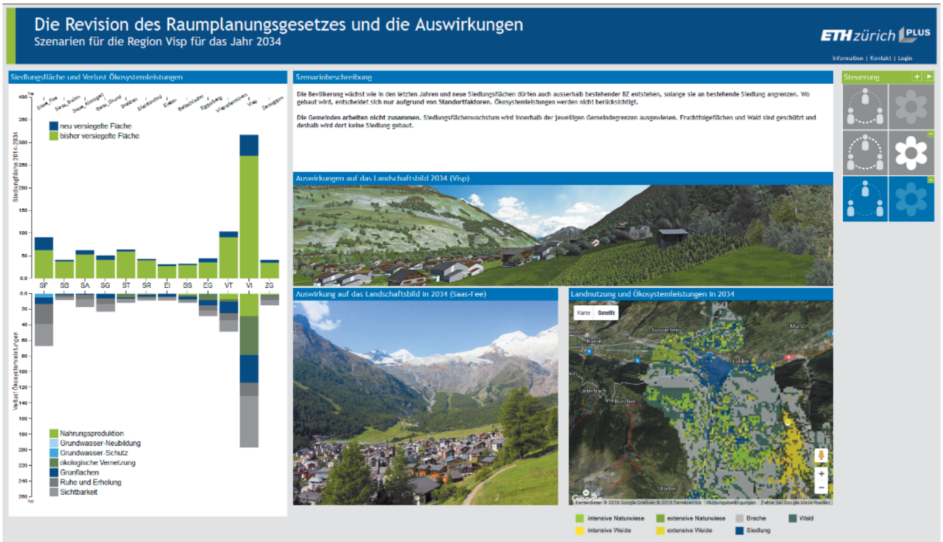

Figure 20 - DSS prototype providing information about future landscape developments with/without consideration of ES related to various scenarios concerning different settlement areas depending on the policy instruments.

ten stakeholders with different expertise participated in the workshop. Their expertise varied from environmental protection, agriculture, forestry, and communal administration to landscape development and planning.

We started the session by introducing the topic, information, and DSS functionalities, after which the stakeholders were split into three heterogeneous groups and given the task of investigating and discussing the provided scenarios by applying the DSS-embedded information, and ultimately choosing between two scenarios: one in which ES are not considered and one in which ES are considered. Both options were definable by the DSS user interface. Four stakeholders were seated together near a machine that displayed the DSS to motivate group discussion and the sharing of heterogeneous knowledge within the groups. Furthermore, the three groups were guided or supported as necessary by a moderator while they applied the provided DSS to clarify any doubts related to the handling or reading of the provided information. In a final plenum session, the findings and preferred scenarios of all the groups were discussed. Throughout the sessions, the users' behavior was observed and subjected to protocol in order to investigate the application and usability of information integrated in the DSS. Generally, the observation and protocols of the group sessions in which the stakeholders applied the DSS show that there exist three application types for the DSS: groups oriented their discussion on the DSS content (1) by either strictly basing their cognitive processes and reasoning on the provided information, (2) by using the provided information as a kick-off for

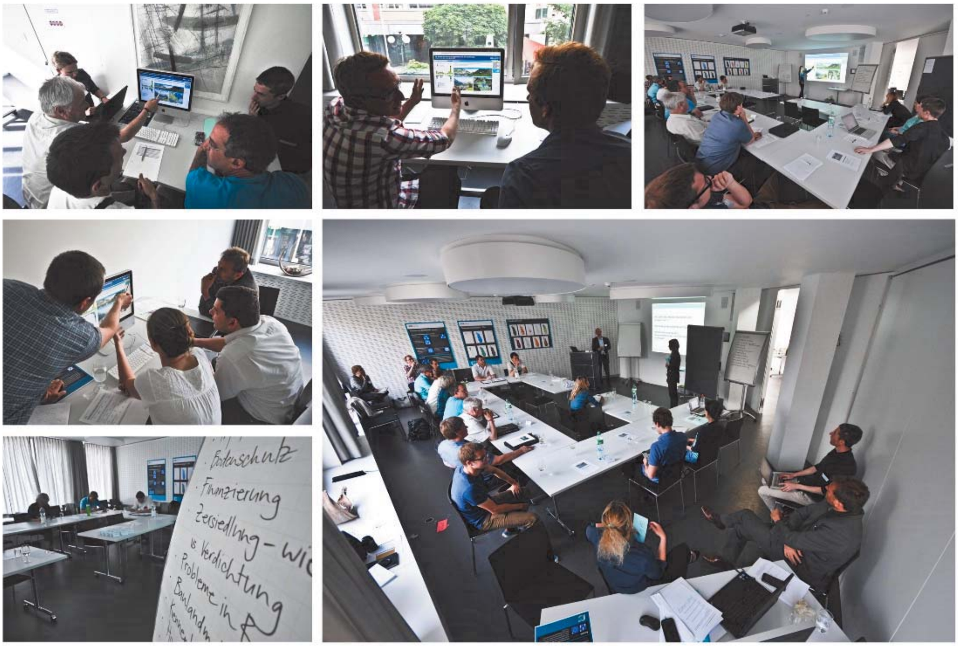

Figure 21 - DSS prototype application in a workshop conducted in May 2015 in the city of Visp (Canton Valais, Switzerland). Users applied DSS-provided ES information via various strategies in group sessions and a final plenum discussion.

discussions that reflected regularly back to the DSS to give the discussion new direction, (3) or by ignoring the DSS and using it only as a trigger for reasoning although the provided information framed the discussion. The latter behavior can be explained by the groups' strong proficiencies in this topic and their spatial knowledge, but it is unclear how these characteristics influenced other group members, such as their behavior while in group settings, especially when considering social psychological effects, which could bias participation and communication in the group, for example, an individual's strength of character and social pressure (e.g., Ash, 1955; Ash, 1956; Granovetter, 1978; Dixit and Nalebuff, 1997). In addition, such dynamics in group behavior could further affect individual choices and theoretically affect policy decision making (Noelle-Neumann and Peterson, 2004; Lazarsfeld et al., 1968). However, group behaviors showed that, in general, the DSS created a willingness to understand the effects on ES depending on the scenario's constraints. Furthermore, the focus on the discussions of ES impact in various scenarios revealed a learning effect in most users. This effect was especially identified, for example, at specific sites (i.e., municipalities) where the discussion focused on various zoning options for new settlement areas.

Overall, the DSS supported efficiency at the workshop and represented a common information base. In the final plenum discussion session, all the groups linked their decisions to the DSS and based their reasoning on the provided information to conclude their scenario choices. However, as the results of a questionnaire distributed at the end of the workshop revealed, some information provided by certain DSS-embedded representation types were considered more important than others, but the preferences of the participants showed high variation. Charts that contained information according to municipalities were mostly preferred, and maps were only used in combination with the chart information. This result was foreseeable, as previous research showed similar findings (*Chapter IV, V*), and DSS user information—representation type preferences—depends on the user's application of the information which relates, in this workshop situation, to scenario assessments. However, a very heterogeneous set of representation types were considered as supportive according to the findings of the questionnaire, which is also in line with the previous results and therefore further emphasized the quality of the demand analysis (*Chapter IV*) and usability testing (*Chapter V*) results.

Furthermore, stakeholders requested information about ES in the case study region, which was not provided in the DSS. Specifically, they requested for information regarding the quantification of ES, about spatial differences concerning ES in the total region, and about efforts for reducing the total damage to ES. Such information was requested mainly by stakeholders who used ES information to look at current and future settlement areas (compare Figure 20) and who preferred landscape visualizations that provided scene quality information concerning the impact of future settlement areas. This request can be linked to a possible mismatch in scale and aggregation by representation types. On the one hand, stakeholders could not place the provided information in the context of the entire case study region, as ES information was filtered by municipalities. On the other hand, the stakeholders tried to also consider aesthetic aspects in their decision making, but the field of view provided by the two 3D landscape visualizations was restricted to two sites. Therefore, an aesthetic assessment was not possible for the total case study area. One stakeholder criticized the readability of the land use map and the scale by stating that it was too small; but they found the land use map, as well as the information about the settlement area, landscape visualizations and the scenario description relatively helpful. However, another stakeholder described the land use map and the landscape visualizations as too abstract, and asked for concrete case study information at the parcel level. All the other sources of information were rated as helpful by these stakeholders. One stakeholder called one of the landscape visualizations "wrong" and would have preferred such type of information for other municipalities as well, as the land use map could not provide a realistic field of view as the landscape visualizations did.

Besides these concrete comments on the provided information, stakeholders additionally provided feedback on missing information in the questionnaire. For example, some stakeholders suggested that information should be added on the current political strategies of the municipalities and any changes in taxation. Other stakeholders found that the emotional and social aspects of the information were missing, but it was unclear what features they were referring to in the feedback. In general, however, the stakeholders did not find the information too complex, with the exception of one stakeholder who stated that the ES information could potentially be rather difficult for non-experts to understand.

7.4. Approach limitations

Although advanced findings (*Section 7.3*) have confirmed the results of the demand analysis (*Chapter IV*) and usability tests (*Chapter V*), it needs to be stressed that requirements engineering approaches exclusively provide feedback on samples that are not necessarily representative of all kinds of DSSs. While the methodology of this thesis underlines the power of requirements engineering for ES information and DSS provision, it should be noted that changing the conditions of stakeholders, users, and case study properties, as well as the DSS features, could affect the requirements of the ES information. Conversely, the usability and supportiveness of ES information with its characteristics are sensitive to users' characteristics, site-specific attributes, situation settings in applications, and embedded framework characteristics provided by DSS characteristics and features.

7.5. Future research directions

This Ph.D. thesis presents new insights on the topic of visual communication of ES, the use of DSS components to support ES trade-off assessments, and provides a novel toolkit called "LANDSCAPEization." This thesis also reveals limitations that point to the need for future research and development.

Supportive ES information provision and its successful communication require comprehensive consideration of various aspects that make information readable and understandable for the audience. The identification of such aspects in this thesis was based on requirements engineering methods, which seem to be a powerful tool for framing information, apart from software engineering. However, based on the feedback of the participants, the conducted analyses and findings were still limited. Identifying project or goal-specific user demands, i.e., how ES information needs to be represented to provide supportive information in various projects, would strengthen and/or reflect the findings presented in this thesis. Identification of such case-specific requirements could provide stronger evidence for the type of ES information needed and, therefore, guarantee the provision of user-tailored DSSs while also creating a positive user experience.

CES assessments tools still have limitations (e.g., La Rosa et al., 2016). Such an imbalance across ES categories consequently means that a trade-off and effective decision making for sustainable landscape development cannot be guaranteed (e.g., Haase et al., 2014; Riechers et al., 2016; Daniel et al., 2012; La Rosa et al., 2016). We showed that DSS usability testing by embedding more detailed and diverse CES data in combination with other ES categories can improve users' understanding of trade-off and decision making related to ES information. However, due to a lack of clarity about CES definitions (La Rosa et al., 2016) and the limited availability of CES assessment approaches, the presented LANDSCAPEization tool only provides a single option in this matter. While more effort is required to develop approaches for CES evaluation, consistent CES definitions are required to enable comparison between studies.

For sustainable development of our future landscapes, landscape design and planning processes need to consider actual landscape characteristics with their (1) environmental processes and (2) visual characteristics (Nassauer, 2012). The developed LANDSCAPEization tool is the first step to providing such a sandbox for planning future landscapes. The design feature could however be improved to support landscape designers in creating future landscapes and providing ES information, similar to the currently developed features in the field of Geodesign (Wissen Hayek et al., 2012b): there is ongoing research on the development of workflows for modifying conditions, manipulating the environmental context, or creating new designs and therefore simulating and examining new landscapes (Ervin, 2011). Understanding ES trade-offs using various approaches at different scales can in addition provide an understanding of the robustness of the assessment (Grêt-Regamey et al., 2014). The LANDSCAPEization tool as such can then be used to operationalize a tiered approach suggested for mapping ES under Action 5 of the Biodiversity Strategy (Grêt-Regamey et al., 2015).

Another vision for further research would be to develop a modeling interface for the LANDSCAPEization toolkit to enable a direct link to modeling approaches, for example, agent-based models, allowing direct visualization and communication of scenarios in real time (e.g., Celio et al., 2015; Brunner et al., 2016). Such efforts have been shown to be beneficial for helping users understand the scenarios and the indicators, as indicators can influence landscape aesthetics (Klein et al., 2013; Klein et al., 2012). However, enabling such real-time visualization and communication of scenarios also requires a real-time modeling approach.

Novel virtual reality (VR) or augmented reality (AR) technologies, for example, Oculus Rift (www.oculus.com), would provide users a fully immersive landscape perception via a visual-acoustic experience. This could improve the realistic perceptions. Studies have already shown (Manyoky et al., 2016) that providing acoustic data in addition to visual information of sites potentially influences the perception and therefore the assessment of landscapes. In the context of CES, which are assessed by users in a normative manner, these technologies offer the novel possibility of letting users experience a place of which they have no knowledge in an immersive and emotional way.

A further vision for future research would be to link this toolkit to virtual games to gain an understanding of player strategies in an ES context. Additionally, to enforce real emotions, the game design could integrate real player profiles or characteristics. For example, the game board with its land use portfolio is automatically projected and cropped to players' real home (e.g., by a virtual globe as provided by Google Earth). Game actions would therefore be based on players' cognitions in the context of their real living homes and environments, and thus, the strategies, trade-offs and decision making would be realized in their own backyards. Such playful handling with ES, as provided by an ES-based game, could establish learning effects in the context of players' living environment and ecosystems and could further contribute to public awareness and mainstreaming of the ES concept.

7.6. Final comments

The outcome of this thesis supports the generation and provision of decision-supportive ES information for planning situations. The demand survey can be used for the general identification of user needs for ES information and for supporting tailored information processing for effective communication in other contexts. Furthermore, the demand survey helps to prioritize DSS components and make necessary adjustments in order to provide relevant information via suitable representation or visualization types. This allows users to read ES information in a comprehensible way and to make sound decisions. In order to also consider CES and enable the exploration of trade-offs among various ES, the LANDSCAPEization toolkit was developed to provide a generic workflow for DSS and ES information provision. The workflow has new interfaces for linking the databases of ES and other indicators, such as plant characteristics, and offers more transparent and credible landscape visualizations due to the possibility of inspecting underlying information. Furthermore, this improvement in landscape visualization production workflow allows the provision of faster, easier, and more realistic visualizations beside participatory mapping and rating functionalities for CES assessments. Thus, trade-offs among ES categories can be explored. In this way, the findings indicate the need for an ES information-based decision-making process which allows special consideration of cultural values. The resulting recommendation of this thesis is to support targeted DSS development with suitable ES information visualization and representation types in planning processes.

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Appendix A

Interactive 3D visualizations

Understanding ecosystem services trade-offs with interactive procedural modeling for sustainable urban planning

Abstract

Given the accelerating rate of urbanization worldwide, the sustainable provision of urban ecosystem services becomes increasingly important for the growing number of city dwellers. Attempts to increase a single ecosystem service however often lead to reduction or losses of others. For making sound decisions about sustainable urban development, knowledge and awareness of the interactions between ecosystem services are thus necessary. In this paper, we show how interactive rulers embedded in a 3D GIS-based procedural modeling environment can assist in making urban ecosystem services trade-offs explicit for sustainable urban planning. The interactive rulers are slider bars that offer stakeholders the possibility to explore trade-offs in ecosystem services reflected in different urban designs. The approach is illustrated in a case study in Abu Dhabi, Masdar City, a new city designed from scratch. An interactive 3D visualization approach links parametric shape grammars for the design of generative urban patterns and the reporting of urban ecosystem services. We show how various urban design scenarios can be generated in an interactive manner allowing a balance between the aesthetics of the urban designs and a set of indicators describing the provision of relevant ecosystem services. With this approach, the space for actions and behavioral alternatives become explicit – a crucial step for sustainable urban planning which calls for innovative strategies to adapt to these uncertain and rapid changes.

1. Introduction

Despite covering only 2.7% of the world's surface (United Nations, 2008), cities are responsible for 75% of the global energy consumption, and 80% of greenhouse-gas emissions (Ash et al., 2008). In the face of today's rapid urbanization, new solutions in urban planning are strongly needed worldwide. From resilient buildings to alternative transportation systems, distributed and renewable energy systems, water-sensitive design, and zero-waste systems, new cities like Masdar in Abu Dhabi (United Arab Emirates), redeveloped areas like Treasure Island (San Francisco Bay, California, United States of America), the New Housing Redevelopment project (Freiburg, Germany), the Hanover Square Redevelopment project (New York City, United States of America), BedZED (Beddington Zero Energy Development), and the new Olympic village in London (Great Britain), are dramatically reducing their ecological footprints. Yet, the consideration of natural urban ecosystem contributions to the quality of life of urban citizens is becoming increasingly difficult under the growing development pressure. Inappropriate policies and ineffective planning neglecting environmental aspects are supporting environmental degradation rather than sustainable urban development (UN-Habitat, 2011).

Natural urban ecosystems provide a wide range of ecosystem services (ES) contributing to public health and increasing the quality of life of urban citizens (Bolund and Hunhammar, 1999). Chiesura (2004) summarizes results of studies showing that the presence of natural assets (i.e. urban parks and forests, green belts), and elements (i.e. trees) in urban contexts contribute to the quality of life in many ways. Besides important regulating services such as air and water purification, noise reduction, and rainwater drainage, natural urban ecosystems provide important cultural values, and increasingly also support food production. While principles used for managing or enhancing the provision of ecosystem services can be applied to these natural urban ecosystems, a greater understanding of people–wildlife interactions, and the importance of landscape features in local areas including the dynamics of exchanges between urban and rural areas are necessary in an urban setting (Savard et al., 2000). In the context of climate change, urban green spaces can play a central role in both climate-proofing cities and in reducing the impacts of cities on climate (Gill et al., 2007). Though the role of green areas in sequestering carbon is small compared to carbon dioxide emissions produced in cities, urban green spaces reduce energy consumption and thus also carbon dioxide emissions by reducing the need for air conditioning in the summer and the need for heating in the winter (James et al., 2009). Yet, in our resource constrained system, attempts to increase a single service often lead to reductions or losses of other services – in other words, they are "traded-off" (Rodriguez et al., 2006; Tallis et al., 2008). For making sound decisions about sustainable urban development, knowledge and awareness of the interactions between ES are thus necessary in order to make nuanced value based judgments regarding such trade-offs (Bennett et al., 2009). Because of lack of information on interactions among ES and as many ES have no market value, trade-offs and synergies are usually not negotiated effectively. Particularly the consideration of cultural services has been considered as difficult because of their characteristics as being "intangible" and subjective, thus difficult to quantify in biophysical or monetary terms (Daniel et al., 2012).

Deliberative decision methods, such as multi-criteria analyses or citizen juries, offer tools for negotiating ES without requiring the monetization of what may regard as intrinsically nonmonetary values (Carpenter et al., 2009; Gregory et al., 2001). A key factor in the success of such tools is the transfer of the relevant information to decision-makers in a credible and comprehensible manner (Wissen et al., 2008). When combined with visual representations, preference assessments can be improved significantly (Bateman et al., 2009). Virtual decision environments have been suggested for controlling variables within a decision context made real by salient inducements (Bishop et al., 2009). Interactive and immersive 3D landscape visualization tools combining visual and non-visual information seem to be valuable for assessing different landscape change scenarios in workshops (Salter et al., 2009; Wissen Hayek et al., 2010), and recent developments in virtual scenario generation have shown how people can explore future options via 3D visualizations and (agent-based) scenario development software (Kwartler, 2005). Stock and Bishop (2005) linked GIS to a realistic 3D model to show, in real-time, visual and environment effects of land use change in a rural context.

Parametric procedural modeling approaches using shape grammars offer powerful city modeling and visualization tools enabling quick visualization of complex city models, evaluation of alternatives, and iterative design workflows. The term "shape grammars" first appeared in Stiny and Gips (1971) and describes one of the earliest algorithm systems for creating designs directly through computations with shapes, rather than indirectly through computations with text or symbols. Shape rules generate designs using shape operations of addition and subtraction as well as spatial transformations on shapes. The actions of multiple rules are coordinated in shape grammars. Parametric shape grammars are an advanced form of shape grammars allowing more of the context of the existing shapes to be taken into account in form of parameters. This typically affects internal proportions of the new shape so that a greater variety of forms can be created. Shape grammars have been implemented in architecture, such as the Palladian Villas (Stiny and Mitchell, 1978), Frank Lloyd Wright's prairie houses (Koning and Eizenberg, 1981), and Alvaro Siza's houses at Malagueira (Duarte, 2001). Müller et al. (2006) introduced an attributed shape grammar called CGA (Computer Graphics Architecture) rule shape grammar, which is the base for ESRI's CityEngine System (ESRI, 2012). Using sequential grammars, CGA shape grammars allow for the spatial distribution of features and components. Ulmer et al. (2007) and Halatsch et al. (2008a) extended the system with urban planning and landscape rule sets. Beside application in urban planning process for understanding and encoding urban patterns (Alexander et al., 1977), and generating sustainable urban designs (Halatsch et al., 2008b), parameterized procedural models have also been used in plant ecosystem modeling for simulating complex scenes with thousands of plants (Deussen et al., 1998).

In this paper, we show how interactive rulers embedded in a 3D GIS-based procedural modeling environment can assist in making urban ES trade-offs explicit for sustainable urban planning. The interactive rulers are slider bars that offer stakeholders the possibility to explore trade-offs in ES reflected in different urban designs. Implemented in interactive software, the rulers can either be controlled by mouse, keyboard, or touch screen or by a virtual remote tool. The approach is illustrated in a case study in Abu Dhabi, Masdar City, a new city designed from scratch. An interactive 3D visualization approach links parametric shape grammars for the design of generative urban patterns and the reporting of urban ES. We show how various urban design scenarios can be generated in an interactive manner allowing a balance between the aesthetics of the urban designs, water consumption and costs, and the provision of relevant ES in Masdar City, namely climate regulation, and habitat for flagship species. The results are followed by a discussion of the advantages and shortcomings of such an approach for sustainable urban development considering the provision of relevant urban ES.

2. Materials and methods

2.1. Interactive procedural modeling workflow

The interactive procedural modeling resulting in computer generation of 3D urban designs accompanied by reporting of urban ES draws upon a parametric procedural approach. Figure 22 shows the workflow comprising three steps: (1) encoding shape grammars, (2) 3D procedural modeling, and (3) interactive pattern valuation, which are elaborated in the next paragraphs.

We first briefly introduce the main concepts of CGA shape extended for encoding urban open spaces, but refer the reader to Halatsch et al. (2008a) for a more comprehensive description. The CGA shape framework consists of shape definition, production process, rule notation with shape operation, and an element repository:

Shape definition: A shape A consists of a geometry, a symbol, and attributes. The most important attributes are the position P, three orthogonal vectors X, Y, and Z, describing the Cartesian-coordinates, and a size vector S.

Production process: The production process starts with an arbitrary configuration of shapes, called the initial shapes, and proceeds as follows: (1) Select an active shape with symbol A in the set, (2) choose a rule with A on the left hand side to compute a successor for A resulting in a new set of shapes B, (3) mark the shape A as inactive and add the shapes B to the configuration and continue with step (1).

Rules: The CGA Shape production rules are defined in the following form: *id: predecessor: condition → successor: prob*

where *id* is a unique identifier for the rule, *predecessor* is a symbol identifying a shape that is to be replaced with *successor*, and condition is an optional guard (logical expression) that has to evaluate to

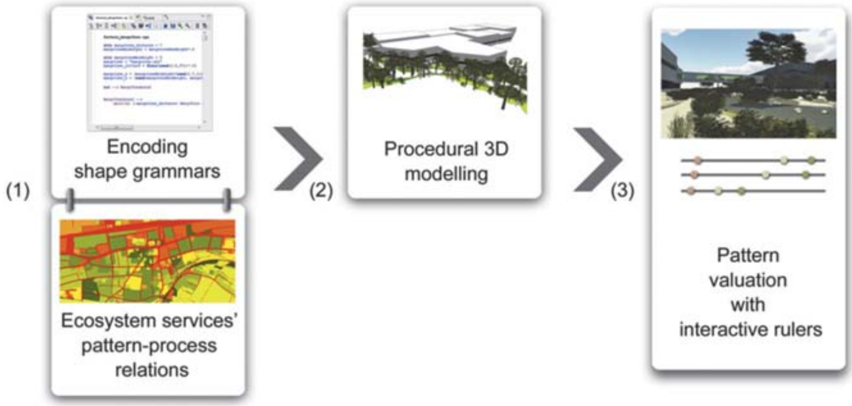


Figure 22 - Interactive procedural modeling workflow for assessing urban ES trade-offs including (1) encoding shape grammars based on design specifications and landscape ecological pattern-process relations for quantifying ecosystem services, (2) GIS-based 3D procedural modeling, and (3) pattern evaluation with interactive rulers showing ES provision.

true in order for the rule to be applied. To make designs stochastic, the rule is selected with probability *prob* (optional). Known relational functions of confirmed geometrical and spatial configurations such as street types can be organized in hierarchical rules and are called *design patterns*.

Shape operations: 2D shape operations include subdividing objects along an axis, splits which can divide a shape into its geometric components, and repetitions of the operations. 3D operations can be applied to modify the successor shape like translating or scaling.

Element repository: The library of 3D models consists mainly of basic primitives, elementary architectural objects and plant models. The elements are hierarchically organized in categories and types and each element has a unique identifier, a set of attributes and metadata.

2.1.1. Encoding shape grammars

When encoding shape grammars, rules between shapes and spatial patterns need to be defined. Following the landscape ecological pattern-process relation concept of Nassauer and Opdam (2008), we define the relationships between species and the spatial distribution of species based on determined requirements concerning the provision of ES. Organized into basic design patterns, the landscape elements and their spatial patterns are encoded into rule sets structured in shape grammars. Stored within a pattern text file, the grammar rules describing each design pattern form the base for the procedural modeling.

2.1.2. Procedural 3D modeling

For the generation of the GIS-based 3D visualizations of urban designs, the shape grammars need to be implemented in a procedural modeling software. In this contribution, we used CGA shape grammars that are implemented in ESRI's CityEngine system (see Halatsch et al., 2008a; Ulmer et al., 2007). It can process urban environments of any size ranging from a single lot up to a whole city. The input data to the procedural modeling software are GIS data such as building footprints, main streets, and parcels. These initial shapes (usually polygons) are fed into the grammar engine, which generates designs by applying the selected rules. Design specifications instructing the general layout of different space types can often be extracted from master plans. The resulting model can then be previewed in the OpenGL viewer of the CityEngine or can be photo-realistically visualized in a 3D application such as Vue (E-Onsoftware, 2012), suitable to create landscape visualizations with high level of detail and visually realistic effects of, for example, atmospheric conditions, shading and light reflections. Thus, while abstract 3D visualizations (for an example, see Figure 25) can be generated in real-time using the procedural pattern generation with CityEngine, photo-realistic urban designs (for an example, see Figure 26) need to be rendered in a decoupled manner with additional software.

2.1.3. Interactive pattern valuation

A series of sliders linking urban designs with ES provision and indicators providing more information about the urban design (e.g. costs, type and amount of landscape elements, and water consumption) allow the users of the interactive platform to understand the trade-offs between the aesthetics of the design and the amount of ES and other indicator values. Changing indicator values or the value of the ES leads to a change in spatial patterns and the related 3D visualizations of the urban design. As one can generate many urban designs with different combinations of indicator values and ES, we used a conjunctive screening rule (Hauser et al., 2010) for reducing the number of options presented to the user of software platform. Selected options included all the combinations which had acceptable levels for all parameters. The levels of acceptance were subjectively assessed. The interactively available number of aerial and ground-level viewpoints allowed the user to change viewpoints at will, while also interacting with the possible solutions via the sliders controlling the level of emphasis on the values. If one aims at presenting photo-realistic visualizations in real-time to the user, a database of pre-rendered urban designs linked to their input data need to be generated as the rendering process is currently too slow. In this contribution, we organized the data in YAML markup, and imported the pre-rendered urban designs linked to their input data in CSV format. Loaded by a JavaScript application running in a browser, which creates the interactive rulers used to manipulate the indicator and ES values, the pre-rendered designs could thus be swapped in realtime.

2.2. A case study in Masdar City

2.2.1. Masdar City

Abu Dhabi's success and fortune rose enormously in the 20th Century with oil production. In order to secure its future as a leader in energy production, the Abu Dhabi Future Energy Company has been set up to investigate and champion new ideas for energy production. The Masdar Initiative was established in order to discover approaches for meeting the world's growing energy need: A new zero-carbon emission city, Masdar City, is planned in the subtropical desert near Abu Dhabi (Foster + Partner, 2009). Comprising an area of 650 ha and a target population density of approx. 135 people per ha, it will become an ecocity of the future that will be only dependent on renewable energy. Masdar City is located at Latitude 24°28N and Longitude 54°22E, which is just North of the Tropic of Cancer in a subtropical desert environment. The subtropical climate is characterized by sunny weather and infrequent rainfall. April to September is generally hot and humid with maximum temperatures averaging above 40 °C. During this time, sand and dust storms occur intermittently, in some cases reducing visibility down to a few meters. Furthermore, two key factors are predicted to increase the local temperature by 2.4 °C over the next half century (Foster + Partner, 2009): (1) In the coming decades, a high level of urban development in and around Abu Dhabi is expected, affecting the local climate due to changes in land surface characteristics, and (2) the Intergovernmental Panel on Climate Change predicts an approximate 0.5–3.5 °C increase in global air temperature over the next century, depending on numerous factors including the magnitude of greenhouse gas emissions.

Providing Masdar City with water is thus one of the most difficult tasks. To achieve a target of 180 l/day/person compared to an average of 550 l/day/person under a business as usual scenario, the city is using a broad array of water-use reduction technologies and systems. While evapotranspiration from vegetation or water surfaces and/or shadowing by vegetation become relevant processes for maintaining thermal comfort, trade-offs between water availability and ES-based microclimate regulation become key factors in planning (Shashua-Bar et al., 2009).

Besides considering waste, energy, water and transport infrastructures as well as other contributing aspects such as lifestyle, cultural heritage, climate and biodiversity, the master plan of Masdar City describes design guidelines for urban green space (Foster + Partner, 2009). They include descriptions of the design of green spaces surrounding buildings and contributing to the creation of a pleasant microclimate through the vegetation, particularly as shading, and specify the need to use drought tolerant indigenous and Mediterranean plants. In this study, we focus on the design of the "Linear Park" (2.5 ha) located in the core zone of Masdar (Figure 23). It runs through the Swiss Village (12 ha), which is currently in construction, and in which Swiss companies will promote Swiss technology, design, and quality (SVA, 2009).

2.2.2. Urban ecosystem services

The selection of ES to be further considered in the case study was based on the results of a literature review on relevant urban ES with a focus on ES that can be provided by green spaces in courtyards under subtropical climate conditions (Table 8). Most important ES provided by green spaces in Masdar City include micro-climate regulation, habitat, and cultural ecosystem services. Though water regulation services such as groundwater infiltration for water storage would be important in the environmental conditions found in Masdar City, infiltration of water into the ground is not given, as the entire city is built on an underground transportation system. Furthermore, water collection systems are not considered in the case study, as they are mainly man-made.

Table 8 - Urban ecosystem services relevant in Masdar City.

MEA category	***Urban ecosystem services***
Regulating services	
Micro-climate regulation	Moderating local air temperatures, cooling (through evaporation and shading) (Shashua-Bar et al., 2009) Radiative cooling of vegetation surfaces (Foster + Partner, 2009, p. 116)
Water regulation[a]	Water infiltration (urban hydrology model, storm water run-off) Water condensate collected on radiation cooled surfaces (water resource) (Foster + Partner, 2009, p. 116)
Habitat services	Connectivity Habitat for flagship species (Longcore et al., 2004)
Cultural services[b]	Landscape aesthetics Recreational activities Cultural heritage Spiritual and religious significance

[a] Water regulation services were not included in this contribution as they are mostly man-made in Masdar City.
[b] Only visual landscape aesthetics were considered in this contribution in a simplistic manner by linking landscape elements with 3D visualizations of the urban designs (see text for more information).

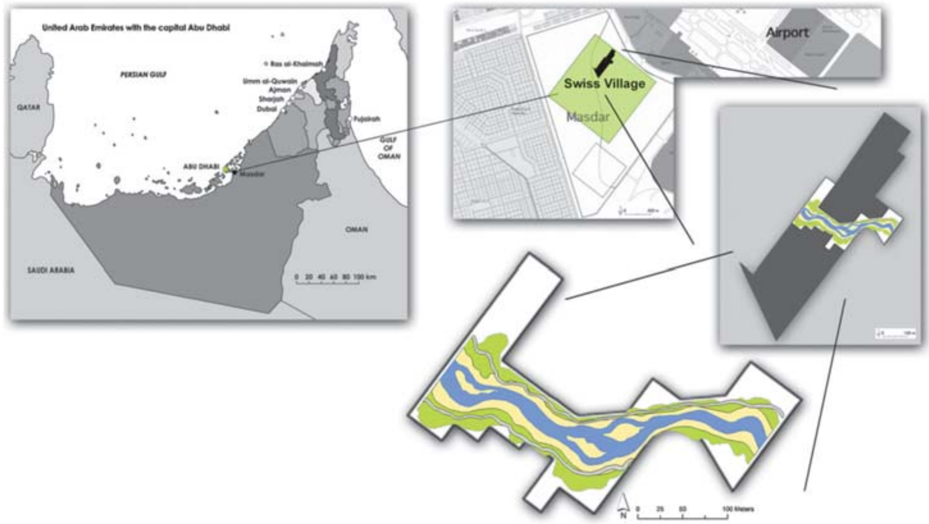


Figure 23 - Location of the Swiss Village in Masdar City, Abu Dhabi, United Arab Emirates (map source: SVA, 2009). The Linear Park running through the Swiss Village is represented in the right inset.

While we only included micro-climate regulation and habitat as ES in this contribution, we made a first step in assessing visual landscape aesthetics by linking landscape elements with 3D visualizations of the urban designs, allowing the user to immerse into the area. The urban designs were based on design specifications of public areas described in the master plan of Masdar City, which states the high importance of aesthetic qualities of green spaces and links the design specifications to the provision of diverse recreational activities. Though computer visualizations of changes in landscape features are known to support empirical models to assess the perceived aesthetic consequences of those changes (e.g. Arnberger and Eder, 2011; Bishop and Lange, 2005; Meitner et al., 2005), obtaining a relationship between landscape elements and aesthetic values would require a perceptual survey, which was not conducted in the frame of this study.

2.2.3. Implementing the procedural modeling workflow

Shape grammars were encoded for each ES and each indicator based on relationships between landscape elements and environmental parameters described in the next paragraphs. Table 9 summarizes the parameters used for encoding the shape grammars. The selection of animal and plant species was based on the Masdar design specifications for open spaces (Foster + Partner, 2009).

Micro-climate regulation and water consumption: The cooling effect of vegetation within an urban context depends on the vegetation type and the irrigation regime,

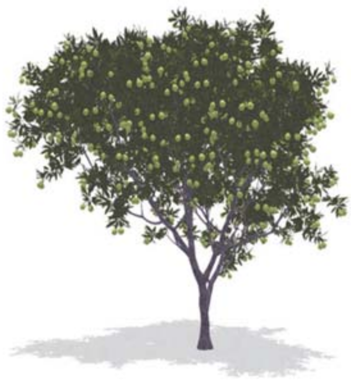
Table 9 - Parameters used in the procedural modeling.

Ecosystem services	*Landscape element*	*Landscape/ environmental parameters*	*Costs (Euro per unit)*
Habitat services (ha)	Desert Hare	2–5	0
	European Roller	300	0
Micro-climate regulation (sqm shadow)	Tamarisk	7	1
	Orange Tree	78	65
	Mango Tree	78	69
	Lemon Tree	19	82
	Young Fanpalm	19	7
	Medium Fanpalm	28	73
	Adult Fanpalm	113	104
	Lentisk	28	4
	Sauxal	2	0.1
	Lawn (per sqm)	0	4
Water consumption (l/day/unit)	Tamarisk	465	1
	Orange Tree	1142	65
	Mango Tree	1132	69
	Lemon Tree	1170	82
	Young Fanpalm	607	7
	Medium Fanpalm	1469	73
	Adult Fanpalm	1267	104
	Lentisk	751	4
	Sauxal	23	0.1
	Lawn (per sqm)	12	4

the adjacent buildings, and the aridity of the location (Shashua-Bar et al., 2009). On one hand, plant species differ in their transpiration rates depending on their adaptation strategies to habitat, e.g. by regulating the opening or the density of leaf stomata. Maximum evapotranspiration of the plants is only possible if the available irrigation water can compensate for the daily water loss. Quantification of water-consumption for maximum evapotranspiration was based on three sources: (1) an evapotranspiration method based on guidelines for unmetered landscaping water use, which shows how to estimate supplemental water requirements based on the amount of water transpired and evaporated from plants for different climate locations (McMordie Stoughton, 2010), (2) standards of the sustainable buildings practices "LEED – Leadership in Energy and Environmental Design" (U.S. Green Building Council, 2005; van Nieuwenhuyzen, 2011), and (3) climate data of the Environment Agency of Abu Dhabi (2009) implemented in the "WUCOLS - *Water Use Classification of Landscape Species*" (University of California Cooperative Extension, California Department of Water Resources, 2000). The resource consumption indicators of water consumption and costs of irrigation were connected to the amount and size of the trees, bushes and sand or turf areas used in the urban designs. The costs for the plants were based on pricelists of plant nurseries and landscape gardeners (von Ehren, 2008). Costs for the lawn were obtained from Seedland (2012). On the other hand, plants also provide a cooling effect by offering shadow. Depending on leaf density more sun can penetrate to the ground, which is expressed in percentage solar transmissivity. Crown widths and the numbers of trees in each urban design alternative were used to estimate shadow areas.

The selection of the plant species was based on Foster + Partner (2009) and the Environment Agency of Abu Dhabi (2009) suggesting a mix of European, Mediterranean landscaping examples and indigenous vegetation types to communicate the general rules for green space design. Selected tree types ranged from indigenous and drought resistant vegetation, such as tamarisks (*Tamarix*) and sauxals (*Haloxylon salicornicum*), over lentisk plants (*Pistacia lentiscus*), to a vegetation of an artificial oasis with a rich diversity of heat tolerant Mediterranean plant species including citrus trees (*Citrus limonum, Citrus sinsensis*), mango trees (*Mangifera indica*) and fan palms (*Hyphaene petersiana*) requiring high water supply. These tree types were linked to rules defining their distribution over the area and to information about the required structure of the ground cover for optimal growth. In order to give the park a natural appearance, indigenous plants were distributed sparsely over the area, the ground was covered by sand, and stone groups were placed in the river bed (Environment Agency of Abu Dhabi, 2009). In contrast, if more water consumptive trees were selected, the vegetation density was increased and turf was used as ground cover. An example of a CGA grammar used to generate the mango tree distribution pattern and the calculation of micro-climate regulation is provided in Figure 24.

Habitat services: Native habitats in urban areas have considerable social and educational values (Miller & Hobbs, 2002). In addition, explicit biodiversity objectives are given in the master plan of Masdar City in form of defined target numbers of animal species that should find their habitat within the city such as the desert hare (Lepus capensis) and the European roller (Coracias garruous). The European roller is a bird requiring Mediterranean-type, shrubby vegetation in a 300 ha network of inter-connected patches as home range (Angelstam et al., 2004). The desert hare also needs Mediterranean type shrubby vegetation for sheltering from sun and predators (Drew et al., 2008) and grassland for food. His home range reaches up to 300 ha (Flux and Angermann, 1990) with 20 ha of inter-connected patches (Drew et al., 2008). While the Linear Park only provides 2.5 ha, the vegetation corridor links the rural habitats with the urban green areas, thus guaranteeing the minimal home range of the targeted species (Flink and Seams, 1993).



```
Pattern_MangoTree.cga

attr mangotree_distance = 7                                  // defines the tree distance
mangotreeMinHeight = mangotreeMaxHeight*.6                   // min. tree height = 60% of
                                                                max. tree height
attr mangotreeMaxHeight = 9                                  // max. tree height
mangotree = "mangotree.obj"                                  // loads 3d model
mangotree_jitterT = floor(rand(0.5,57))*.01                  // locate trees with slight
                                                                deviation from centre point
mangotree_w = (mangotreeMinHeight*rand(0.7,1))*0.6           // assigns tree width randomly
mangotree_h = (rand(mangotreeMinHeight, mangotreeMaxHeight)  // assigns tree height randomly

Lot --> MangoTreeAreaZ                                       // initial rule that forwards to
                                                                MangoTreeAreaZ

MangoTreeAreaZ -->
    split(z) {~mangotree_distance: MangoTree color("#ccff66")}*
                                                              // split the area according to
                                                              the defined tree distance and
                                                              go on with rule MangoTree and
                                                              assigns a color for
                                                              groundcover

MangoTree -->
    10%:        t('mangotree_jitterT,0,'mangotree_jitterT)    // defines a ten percent
                                                                 Density and translate/move
                                                                 the placement origin
                s(mangotree_w,mangotree_h,mangotree_w)        // set height and width
                r(270,rand(0,360),0)                          // random rotate
                i(mangotree)                                  // insert 3d model

       report("Instance.mangotree", 1)                        // reports the placed instance
       report("ShadowArea.mangotree", mangotree_w*mangotree_w) // reports the potential
                                                                 shadow area through
                                                                 groundcover

else: NIL
```

Figure 24 - Example of a Computer Generated Architecture (CGA) rule for the distribution of mango trees (Mangifera indica) and the calculation of indicators in ESRI's CityEngine. Left: 3D object model of a mango tree. Right: Computer Generated Architecture (CGA) rule defining the distribution pattern of mango trees and giving the equations for calculating the three indicators shadow area, water usage and costs with regard to the total area of mango trees.

The initial shape of the procedural modeling was a sketch of the Linear Park based on the typical Arabian land use type "Wadi", a valley or riverbed that contains water only during times of heavy rain. The concept was digitized in ArcGIS (ESRI, 2012) and the land use types, such as paths, lawns, water areas, were attributed to polygons. The parametric shape grammars were encoded based on the relationships and parameters described above, and implemented in CityEngine for generating design alternatives linked to two indicators, costs and water consumption, and ES values (Figure 25). The photo-realistic rendering and the integration of the various 3D vegetation objects produced with the organic plant modeler Xfrog (Xfrog, 2012) required a pre-rendering of the model outputs.

A database linking the renderings with information about the type and number of landscape elements, water consumption, costs and ES values allowed a real-time visualization of the 3D urban designs of the Linear Park through sliding of the rulers.

Because different urban designs can be generated by the same value for water consumption or for costs, one can assess the possible trade-offs between urban ES and resource consumption by sliding the rulers. Different landscape element combinations can for example be generated requiring the same amount of water at the expense of shadow and habitat for targeted species, or different urban designs can be generated at the same costs providing various urban ES. Realistic options were selected based on a conjunctive screening rule approach as described in Section 2.1.3.

Figure 25 - Abstract 3D visualization of the urban design of the Linear Park in Masdar City generated by the procedural 3D modeling software ESRI's CityEngine.

3. Results

Figure 26 shows the decision-support platform with photo-realistic renderings of three urban design alternatives of the Linear Park. It shows the wide variety of urban designs that can be generated using the landscape elements described in Table 9. The more indigenous design (Figure 26-1) shows a naturalistic concept in which watering is minimized. Without intensive watering, the climate conditions in Abu Dhabi allow only drought resistant plants to survive. The "Mediterranean style" (Figure 26-3) represents the artificial oasis with a rich diversity of Mediterranean plant species, and the "Mixed style" (Figure 26-2) shows a mixed variant between the indigenous and the Mediterranean style with a medium vegetation density, and a combination of different plant species including lentisk plants and sauxals.

Table 10 summarizes the value of the urban ES and the resource consumption values of the three urban designs presented in Figure 26. While the climate regulation effect described by the shadowing effect of trees in the "Mediterranean style" urban design is a factor ten higher than the one of the "indigenous style", the watering costs are more than a factor of hundred higher. Particularly, the watering costs for the large lawn areas in the "Mediterranean style" and the "Mixed style" account for a large share of the costs. In contrast, the "indigenous style" looks quite scant in Figure 26-1 compared to the "Mediterranean style" (Figure 26-3). These two extreme cases with divergent urban designs and related indicator values make the use of such a platform for assessing ES trade-offs explicit. The "Mixed style" shows a combination of the different species and ground covers and a better balance between water consumption and costs. While Figure 26 only shows three possible urban designs and their related indicator values, the platform allows switching between all the different preselected options.

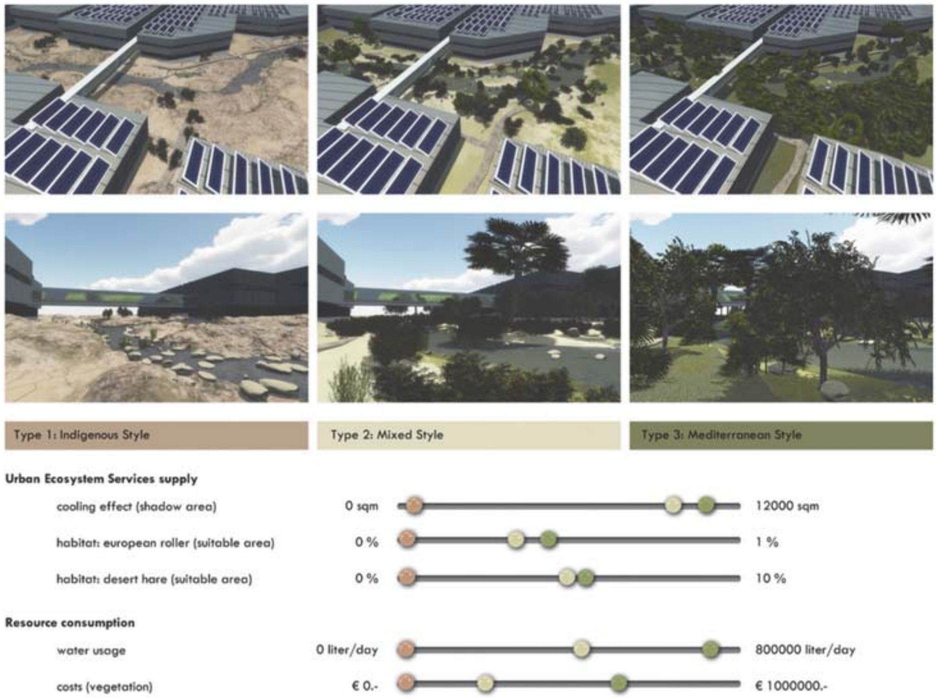


Figure 26 - Photo-realistic renderings of the three alternative design styles (top: overview; bottom: close-up view). The rulers below the visualizations show the indicator values according to the three design styles. The aesthetics are implicitly shown in the 3D visualizations.

4. Discussion & conclusions

Interactive decision making based on information about trade-offs is known to increase confidence in choices (Heath and Gonzales, 1995). Due to lack of information on interactions among ES (Bennett et al., 2009), many trade-offs are however still decided based on assumptions rather than facts (Carpenter et al., 2009; Daniel et al., 2012). Besides monetary valuation, new approaches for resolving complex trade-offs among and between ES are emerging (Daniel et al., 2012). Particularly, when cultural services such as aesthetics have to be weighed against regulating or habitat services, interactive 3D visualization tools linked to GIS-based modeling might become key for explicitly considering often unintentionally ignored ES (Daniel et al., 2012; Rodriguez et al., 2006; Scheffer et al., 2000). Yet, while cultural services strongly depend on perceptions and expectation of the respective stakeholders, considerable conceptual and technical work is still needed to represent and model the complex socio-ecological relationships that define and constrain a given cultural ES adequately.

Table 10 - Indicator report of the urban designs of the Linear Park (2.5 ha) presented in Figure 26.

	Mediterranean style	**Mixed style**	**Indigenous style**
Landscape elements (N)	258	392	134
Shadow area (sqm)	11,593	9995	363
Costs (Euros)	635,270	244,739	1084
Water usage (l/day)	720,841	432,056	5133
Suitable habitat for desert hare (% home range)	5.8	5	0.2
Suitable habitat for European roller (% home range)	0.4	0.3	0.01

Combined with procedural modeling based on CGA rule shape grammars, virtual environments as presented in this study allow making interactive trade-offs between ES including aesthetic values. Using interactive sliders, the user can learn the impact of the selection of various landscape elements on ES trade-offs. While computing limitations required the use of an additional software to create photo-realistic landscape visualizations in this case study, fully featured game engines for independent low-budget game developers have become available at low price (Bishop et al., 2009; Pumpa et al., 2006), and could provide the next steps in such decision support systems. For example, Unity (Unity Technologies, 2012) is a development engine for the creation of interactive 3D content with very high level of detail with regard to the visual landscape representation and high performance enabling smooth walk-throughs of virtual landscapes. Since the engine is open source, model-based virtual landscape development games can be developed offering the potential to interactively weight indicators and exploring the possible landscape changes. Real-time exploration of such virtual environments online is however still difficult due to computing speed, and requires new solutions such as for example the uploading of different levels of details at different locations in the virtual environment. If these problems get resolved, the possible link of such games with various communication engines such as table computers, audience response systems, or mobiles, will foster the involvement of the public in deliberating on landscape changes enhancing the informative content of public's preference assessments (Bishop, 2011).

The interactive rulers become especially powerful, when they can be used in a participatory process utilizing the expertise and knowledge of a broad range of stakeholders assessing the preferences for scenarios. Collaborative planning combining interactive visualization tools with immersive lab facilities have already been explored in other case studies (e.g. Salter et al., 2009). The ability to dynamically explore the visualizations of the planning proposals, and the real-time changes in indicator metrics were considered particularly informative, and appeared to increase participants' understanding of the plan. The application of such an approach in an immersive lab is the next necessary step for evaluating its effectiveness in sustainable planning. Beside an interactive component, the approach also implies an iterative process. This not only allows many stakeholders to be involved, but secures a continuous feedback between future visions and present actions, and offers a learning process also known as "higher order learning" (Brown et al., 2003). This can lead to adjusting problem definition and strategies, changing norms, values, goals and operating procedures governing actions, and thus to an adaptive process in view of the rapid urbanization changes we are expecting. Whereas setting up the presented interactive platform is rather laborious and requires high specialist skills, for implementation in practice the approach can be made more efficient, e.g. by providing packages for ES quantification, a library of landscape elements and vegetation type textures that can be linked to GIS data attributes, and an open source interface for linking the data and making the interactive trade-offs. Once the library and the rulers are set up, one can apply the 3D GIS-based procedural model to the municipality level, where it can deploy its full potential. Furthermore, while extant research on consideration set formation provides evidence that consumers use simplifying heuristics before making a choice (Bettman, 1979), much more sophisticated efficient choice design techniques than the one used in this study are available, and would improve the analysis and evaluation of the preference data (Scarpa and Rose, 2008).

While this contribution only focused on the planning of a small part of Masdar City, the creation of a new city in a desert can cause major ES changes in the surrounding of the planned city. The vulnerable desert environment, in which Masdar City is being constructed, provides a wide range of important ES, especially also for other nearby cities such as Abu Dhabi, in terms of climate regulation services. The presented interactive procedural modeling could also be applied to investigate trade-offs for planning cities from scratch, thus allowing investigation ES trade-offs in an environment with and without the new city. Other applications range from defining various land use plans to selecting locations for new infrastructures. Furthermore, the case study focuses only on two ES, and could be expanded to include a full range of other ES also applicable in other urban contexts. Further rules would thus have to be developed, requiring close collaboration among ecologists, social scientists, urban designers and economists and computer systems developers to identify relevant variables and to develop required models.

In conclusions, despite the current limitations of the presented case study, we demonstrate that interactive rulers embedded in procedural modeling can be a powerful tool for developing alternative urban design patterns. Because of their potential to make trade-offs between urban ES explicit, they broaden the space for actions and behavioral alternatives in sustainable city planning – a crucial step under the worldwide urbanization pressure, which calls for innovative strategies to adapt to these uncertain and rapid changes.

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Detailed information Appendix B:

Original title: Decision Support Systems and Tools as Collaborative Web Platform for Sustainable Development of Landscapes

Authorship: Klein, T.M.; Wissen Hayek, U.; Celio, E.; Grêt-Regamey, A.

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Appendix B

Collaborative web platform

Decision support systems and tools as collaborative web platform for sustainable development of landscapes

Abstract

Landscape development is increasingly characterized by collaborative processes involving multiple stakeholders of heterogeneous groups. An essential prerequisite for effective collaboration and sound decision-making in landscape development is the understanding of participating stakeholders of required landscape information and the interrelationships between factors influencing landscape development. The tools for representing, processing, analyzing and combining spatial data have evolved and diversified enormously in the last 30 years. This has influenced also the set of media that is applied in participatory planning workshops. Current technology offers great opportunities to allow broad access and to support deeper understanding of landscape processes by implementing web-based platforms. These comprise 3D landscape visualizations and spatial analysis functions. However, an analysis on how to prepare these platforms, their technical structure, their user interface, and the spatial data is missing. In this paper we present a technical framework of a collaborative web-based platform that takes into account basic user demands for understanding and evaluating landscape processes. Further, we show an initial prototype of a user interface and its information content that was tested with stakeholders. The evaluation results show that the complexity and amount of information offered by the user interface should be customizable for different user groups. New approaches have to be developed to integrate realistic real-time visualizations into the system. Overall, for securing the final tool's effectiveness, it is essential that the technical development of the system is tight to its implementation in collaborative planning situations. These results provide helpful advice for targeted development of the collaborative web-platform system's components.

1. Introduction

The style of collaborative workshops in land use planning has undergone big changes during the last three decades. These are also related to the development of new communication techniques (Arciniegas and Janssen, 2012). Workshop techniques 30 years ago based on large hard copies of maps combined with sheets of tracing paper maps for presenting characteristics of proposed plans or planning areas. With the implementation of Geographic Information Systems (GIS), a new communication tool was offered that allowed to present various map layers on a computer screen and could partially replace hard copies of (tracing) maps for examination (Longley et al., 1999). A next step, which is still under development, takes into account functions and services or the related policy configurations and connects them with related land use patterns. To reveal these relationships can facilitate a better integration of participating stakeholders e.g. in a planning process (Grêt-Regamey et al., 2013). The workshop style also changed over the years from an emphasis on one-way communication to participation with active stakeholder involvement (Sieber, 2006). Today, the major focus is on collaboration: stakeholders shall actively work together to identify a landscape development strategy that is sustainable and acceptable for the majority of the stakeholders (Arciniegas and Janssen, 2012). But how can we use the existing technologies to support these collaborative processes? How can we prepare and provide spatial data that is accessible, understandable and useful for all participating stakeholders?

GIS-based 3D landscape visualizations have shown great potential as valuable communication tool in planning processes (Wissen Hayek, 2011). Linking quantitative, spatially explicit indicators and realistic 3D visualizations of landscape change scenarios can facilitate the communication of relationships of factors that lead to certain landscape change. This allows to bring in different opinions on a topic and to create public interests (Wissen Hayek et al., 2012b). Furthermore, experiences show that interactive and participative tools help to understand coherence between prioritization of different indicators and possible land use change. For example, in Figure 27 participants of a workshop on wind farm planning choose the priority of economic viability, landscape aesthetics, nature protection, and noise emission. Depending on the indicators' priority, the amount of wind turbines differs. The interactive tool allows users to understand trade-offs between indicator values as well as between different demands of the landscape and landscape aesthetics (Grêt-Regamey et al., 2013).

The variety of planning processes and the diversity of workshop settings and goals complicate the development of an all-purpose decision support platform. The effectiveness of such a platform depends on two major factors. First, it has to provide useful participatory GIS functions, comprising interactive elements of GIS-analyses producing indicators as well as of GIS-modeling producing scenarios of landscape change. Second, it needs to be suitable for participatory settings. With regard to the application, e.g. workshop or self-exploration, the content load and detail of information have to meet the users' demand. Particularly, if the user should understand the relationships between different indicators, overloading the interface is a problem, which can lead to lack of time for appropriate implementation of the tool and even deterrence (Salter et al., 2009). The problem of overloading the interface might be overcome by providing layman and expert modes with a customized offer of spatial information with a useful level of detail. However, there is a

Figure 27 - Real-time modeling and visualizing approach with slider control of selected indicators' priority

general conflict of required detail of information and suitable time investment in collaboration sessions. On the one hand, the need of detailed information on indicators is required to communicate what they state and how they are related to each other. On the other hand, these details need time to be understood. A multi-user group interface might provide a solution for reducing the complexity of available information. However, with this interface type addressing more specific demands of different user groups might become more difficult. In this paper we present a technical framework of a collaborative web-platform system that takes into account basic user demands for understanding and evaluating landscape processes. Further, we demonstrate a first prototype of implementing parts of this system, which was tested in a workshop and at an exhibition with different stakeholders. The prototype was designed to address basic user demands by implementing participative GIS functionality. This included a user interface design with certain interactive functions as well as preparing visual information content according to a defined level of detail and complexity. The evaluation results were analyzed in order to further specify user demands and to discover expected functions of the platform. They provide advice for enhancing the prototype of the collaborative web-platform.

2. Theoretical framework

In the early stages, GIS was used mainly for providing spatial information, but with increasingly active stakeholder involvement and the failure of tracing map paper sheets, a demand of interactive GIS was given. Participatory GIS is designed for improving stakeholder participation within group spatial decision-making (Carver, 2003; Janowski, 2009). Two function types of Participatory GIS must be distinguished: (1) Public Participation GIS (PPGIS) focuses on an enhancement of public access to geospatial data and maps, providing possibilities for participatory learning and analysis by the general public, community groups and marginalized groups in planning and decision-making for their communities (Craig et al., 2002). In contrast, (2) Group Spatial Decision Support Systems (GSDSS) focus on supporting the identification of trade-offs, conflicts and compromises between stakeholder groups (Boroushaki and Malczewski, 2010).

Our hypothesis is that to create an applicable and full-efficient decision support platform, both participatory GIS types (PPGIS & GSDSS) must be combined. Furthermore, the following functions should be available: general information on the planning topic and use of the platform, spatial analysis and evaluation functions, and interactive indicator-based decision support. In the following chapters these three functions are further explained.

2.1. General information content

For understanding complex topics and being capable of evaluation and decision-making tasks, first of all background information must be available and provided in a useful manner. In addition to texts, tables and graphs, maps are the basis for providing relevant information for spatial decision-making. Often stakeholders preferred maps as source of information for spatial decision-making, although they are not easy to understand and use (Janssen and Uran, 2003).

Maps can show various and complex information in a spatially explicit way. They can present alternative solutions, scope for decision-making options or spatial patterns (Kraak and Ormeling, 2003). Further, they can be used for developing scenarios and alternatives, e.g. by drawing in or modifying it (Carton and Thissen, 2009), as well as to handle conflicts among stakeholders. In this way, they can support feedback loops in the planning process (Arciniegas and Janssen, 2012; Andrienko et al., 2007). Another function of maps is that they provide base-layers (e.g. thematic and topographic maps) for the before mentioned functions (Arciniegas and Janssen, 2012). In addition, map information can provide the input for GIS-based 3D visualization of alternative scenarios, which provide a common communication basis and support mutual concept development (Hehl-Lange and Lange, 2005; Wissen Hayek, 2011; Grêt-Regamey and Wissen Hayek, 2013).

2.2. Spatial analysis and evaluation

GIS-based analysis is key for gaining information on the current landscape state or alternative development scenarios. Multi-Criteria Decision Analysis (MCDA) is an effective method to perceive the necessary trade-offs of different demands of the landscape. By weighting different criteria addressing economic viability, ecological or social quality of the landscape, and possible scenarios of landscape change are calculated. Integrating a MCDA in the workflow provides a method to evaluate, compare, rank, map and present the performance of decision alternatives on the basis of several criteria and/or objectives (Malczewski, 2006; Grêt-Regamey and Wissen Hayek, 2013). Ideally, stakeholders with different backgrounds should choose criteria and indicators as well as their weighting themselves. In order to avoid mismatches and misunderstandings between the stakeholders' decision-making problems and the answers produced by the system, it is necessary that constraints are set with regard to the interactive modification of criteria and indicators in the user interface (Uran and Janssen, 2003). This might influence the required user interface complexity.

2.3. Interactive decision support

Depending on the functions of an interactive decision support tool aimed at, a selection and combination of various interactive methods is possible. User-friendly interfaces are necessary to allow multiple users to provide input and generate real-time output for supporting to form an opinion and decision-making (Arciniegas and Janssen, 2012). Interactive exploration and interactive allocation of map content is required to secure credibility and provide information for specific areas of interests. Furthermore, real-time output of analyses and landscape change models is important for dynamically exploring the spatial outcomes. Iteratively testing different input parameter settings and exploring results can facilitate the comprehension of spatial environmental effects. In this context, linking the quantitative, abstract modeling results to more qualitative 3D visualizations interactively is seen as a promising way (Grêt-Regamey et al., 2013; Wissen Hayek et al., 2012a).

3. Methods

The goal is to develop a collaborative web-platform that integrates both types of participatory GIS (GSDSS and PPGIS). We elaborated a general technical framework for such a platform and tested parts of it in order to start its implementation. First, the technical framework is described. Then, the prototype of an interactive tool called "Landscape Impact Assessment Controller" is presented. Finally, the evaluation method of the effectiveness of the prototype is explained.

3.1. General technical framework

The various demands of different user groups call for a dynamic user interface in order to provide a useful decision-support tool. We developed a technical framework that combines modeling and visualization functions essential for interactive landscape impact assessment by different user groups.

Resulting from the literature review essential functions are: (1) The selection of indicators/parameters and their characteristics can be controlled interactively and the related landscape changes can be presented as spatial information. For example, the amount of economic incentives for farmers can be modified and as result the agricultural area that might be managed or abandoned are shown as abstract and realistic 3D visualizations at the area of interest. Thus, the user can identify trade-offs, limitations and restrictions with regard to the choice of the parameters' characteristics. Implementing this functionality requires a real-time user control of the GIS-model.

(2) The GIS-model scripts have to be standardized to make them accessible to different software and thus allows for linking different GIS-models. This standardization of indicator values and labeling, attribute labels, input/output data types, coordinate system, projection, etc. is also necessary for further processing of modeling results, e.g. in visualization workflows.

Figure 28 shows the schematic framework of a decision support system. The system consists of five different servers and three workshop decision-support tools that are the front-end decision support platform interface and peripheral devices and software, such as mobile decision support apps.

The web server is the core of the platform and serves as hub for all applications. All requests and replies pass the technical interface of the web server and are linked to spatial data and mapping information streams like GoogleEarth from the streaming data server. The users interact only through the web platform. Platform inputs, e.g. information requests are forwarded to the GIS-model server. This server runs the requested models and analysis modules (e.g. ArcGIS Server, R-Scripts), queries necessary data from the geodata server and sends the results back to the web server. Produced model outputs are also interpreted and linked to 3D objects and textures for 3D visualization. The resulting 3D visualizations are sent to the web server and displayed on the platform. This workflow is similar to existing ones (e.g. Pettit et al., 2013) with the difference, that we try to integrate a full controllability of models by adapted user interface design.

3D landscape visualization of high detail requires the use of 3D objects for built and natural landscape structures and elements. The standardization of the input and output data of the spatial modeling processes allow for accessing the 3D objects automatically. However, in a library the 3D objects have to be structured in a meaningful way so that their access is secured. For example, a land use pattern of forest is defined by the forest type (e.g. deciduous, coniferous, or oak-hornbeam forest (Carpinion betuli)). This information should ideally already be available in the output of the GIS-model. The forest type defines the plant types of the trees, e.g. for an oak-hornbeam forest there are oak (Quercus robur) and hornbeam (Carpinus betulus), and further plants of the shrub and ground vegetation layer such as anemone (Anemone nemorosa), that are selected by data base queries. Finally, a realistic distribution of the individual plants of the forest type is necessary (Röhricht and Clasen, 2006; Paar et al., 2008).

One major bottleneck is the time required for the real-time modeling processes. Saving produced model outputs to an archive on the GIS-model server allows

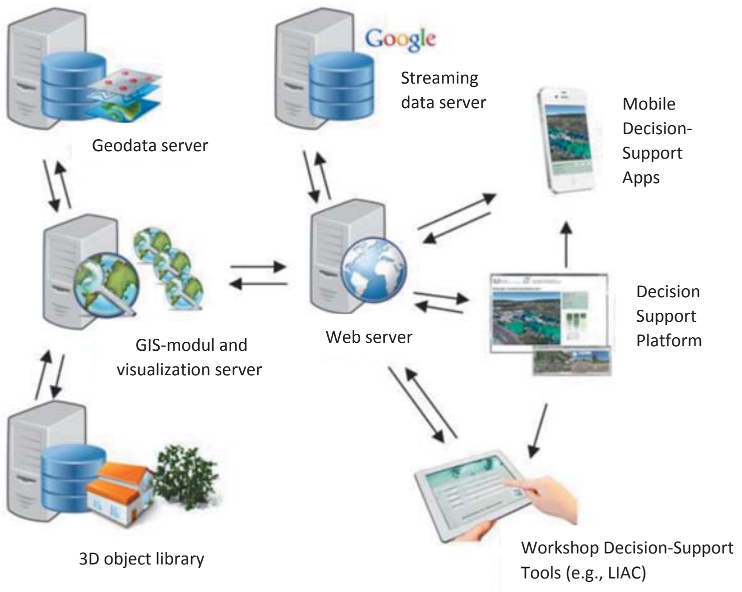

Figure 28 - Schematic framework of a Collaborative Web-Platform Decision Support System for landscape planning

for showing the results immediately on request. This archive option would allow users to share their evaluated scenarios among each other and discuss them for example in group rooms using the platform. The users feed the archive by using the platform and optimize the processing time by enlarging the amount of already processed model outputs. Of course, this procedure makes only sense for time-consuming models and analyses. A further option for achieving a real-time modeling approach is to implement interactive selection methods. Models and associated visualization workflows might then only be run for preferred perimeters. Perimeter selection could be carried out by a list of regional boundaries (e.g. administrative districts) or by designating a user specified perimeter by drawing a polygon on a map.

3.2. Prototype of Landscape Impact Assessment Controlling tool (LIAC)

In order to overcome the problem of different user capabilities and interface design complexity, we developed a first prototype of a decision support tool. A user-evaluation of the prototype should provide us with information on the users' demands and on useful designs of the user interface. Figure 29 shows the multilayer structure of the prototype of the "Landscape Impact Assessment Controlling tool (LIAC)", which was designed to show the relation between indicators and the impacts of defining certain indicator values on land use. The tool is applied in a workshop setting. The target group for our web-platform are experts in land use and landscape development. The survey in the workshop revealed that participants were more heterogeneous than expected. To facilitate a "hands-on" experience for the participants, the thematic direction was leaned at a workshop series conducted in another study area in central Switzerland.

As indicated in Figure 29, the main screen shows sliders with different optional value settings (low to high) for five indicators, which indicate different states of GIS-model parameters. The change of the indicator values is a direct input to a land use change model. A further option on the main screen is changing the view style to an "abstract view" in the second and third screen. In these screens the land use is shown either as a draped raster map on a digital elevation model or as realistic 3D visualization. Screen 2 presents a large view frame of the 3D visualization (realistic and abstract view mode), while screen 3 shows two close-up views of specified areas and an additional graph for information on land use values.

Considering the large amount of possible combinations of the indicators' values and resulting scenarios, visualization approaches that require many manual steps are not advisable. Furthermore, with a rising number of indicators the number of scenarios is increasing exponentially. A direct GIS-model link to the user interface is one solution to produce scenarios in real-time with full controllability of the output. This was not implemented in the prototype yet. Instead, scenario outputs of a GIS-based land use model were prepared as visualizations and graphs, which were linked to the respective indicator value settings that were input to the respective scenario output. Criteria for the land use modeling of the rural, alpine case study area Andermatt in Switzerland were the degree of liberalization of the agricultural market, agricultural incentives for the farmers, farming income, provision of residential area and the degree of implementing a regulation for second homes in Switzerland. All these criteria have an effect on landscape development and interact with each other.

3.3. Evaluation of the prototype

We applied the prototype in the case study area Andermatt in two different settings, at an exhibition stand and in a workshop situation, and evaluated it applying empirical methods. Visitors of the exhibition were motivated to use LIAC by a small survey that also gave an introduction to indicators and their characteristics (Figure 30). About 30 participants explored the tool at the exhibition. The participants were a heterogeneous group including local inhabitants and representatives of Swiss and international governmental and non-governmental organizations from different departments. In open interviews we asked these users about their impression of the tool.

About 20 participants of the workshop were international experts of land use management, spatial planning and nature protection from governmental and non-governmental organizations, private

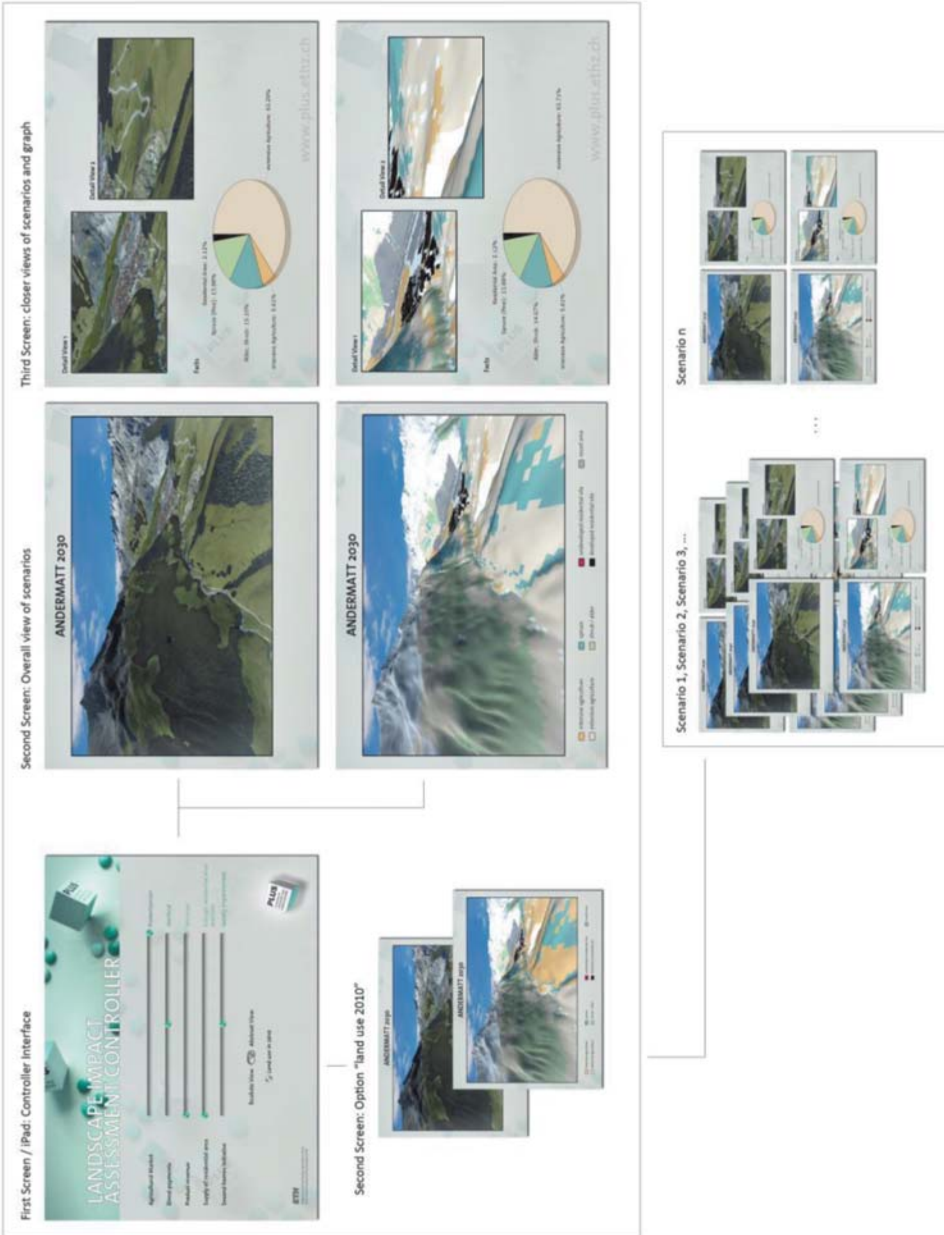

Figure 29 - Schematic screenplay of LIAC (Landscape Impact Assessment Controller), which presents land use scenarios that are defined through the interactive setting of indicator values in the controller interface

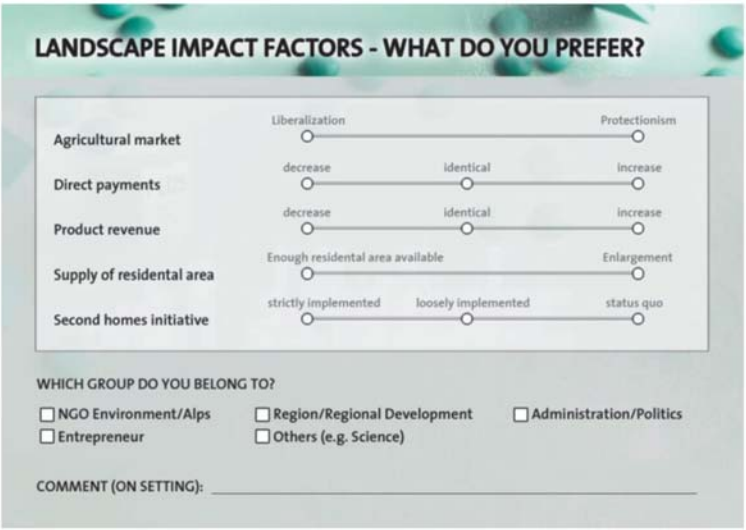

Figure 30 - Questionnaire of the survey carried out at an exhibition stand providing an overview on indicator characteristics and animating visitors to apply LIAC.

enterprises, and academic institutions. They were briefed on the prepared planning topic and the GIS models. In addition, the workshop moderator used LIAC to introduce the participants to the information content as well as the functionality and handling of the tool. The decision tool was controlled by a tablet PC that was synchronized to a projector screen presenting the chosen value settings of the indicators. The idea of this setup was to hand over the tablet to workshop participants for supporting their argumentation or explanations implementing the tool interactively. In a group discussion we received the users' feedback on the potential application of the tool and the quality of the user interface. Furthermore, we observed the users in both settings to record their reactions and if the controlling of the user interface was easy to handle.

4. Results

During a short personal and individual introduction of the available information, the participants at the exhibition "played" with the indicator settings of the LIAC tool to find out how the virtual landscape changes (Figure 31-A, -C, -D). Teenager used the tool more explorative than adults. However, all participants understood that the future land use patterns depend on the five indicators' value settings. The users recognized by themselves, how the indicators influence each other. Furthermore, they recognized on which scale the indicators can influence future landscape aesthetics. For example, less agricultural incentives for farmers effect an abandonment of fields and leads to an increase in forest in certain areas.

In the workshop the participants were rather interested in detailed explanations

Figure 31 - Application of iPad controlled LIAC in self-exploration situations and a workshop situation

of the correlation between indicators than in a self-exploration of the tool (Figure 31-B). In conclusion of the group discussion the participants appraised the tool as innovative and useful as discussion basis in a workshop. However, participants stated that the interface offered too much information on the three screens. Furthermore, they asked for more user control on the models to verify effects and impacts of priority settings. Additionally, the participants mentioned that an interactive navigation through the 3D visualizations would have been desirable to see changes in detail, to have a better overview of the site, and better impressions of the view of the landscape.

5. Discussion & conclusions

The fast developing technical possibilities of providing spatial data in various types of forms and in different types of accessibility offer sophisticated means for supporting public participation in spatial planning. However, combining the available tools to a coherent and powerful system that can facilitate collaboration of heterogeneous stakeholder groups effectively is a major challenge. We focused in this paper on how to prepare a collaborative web-platform and presented a possible technical structure. Stakeholder feedback on a prototype of a user interface and spatial data presentation provided helpful insight for further development of the system.

Generally, the stakeholders were interested in the new means. The users stated that a tool with interactive control of input parameters for generating scenarios of landscape change could help to understand complex landscape issues and offer a new basis for discussion in workshop situations. Even with rather general scenario information the prototype enabled participants to identify relationships of the five indicators controlling the land use change model. But we received also information on missing functions of the tool, which should be available to meet the users' demands.

Obviously younger participants (aged < 20 years) had less fear of contact with the interactive application than older ones. A reason might be that these young people are so called "digital natives" that grew up with the digital technologies (Lange, 2011). Through interacting with digital technology from an early age (e.g. mobile devices, smart phones), they should have a good concept of these tools. The higher reservation of older participants might, however, be ascribed to a more critical examination of the technical means due to larger expert and case knowledge. Their requests for more information on the GIS models indicate that their focus was clearly on the meaning of the tool to provide reliable and thus useful information.

The first feedback of the users of LIAC shows that there is a need for a customized user interface design depending on the user group. In particular, the knowledge and capability of the users is crucial for defining a useful complexity of the user interface design. Overstraining users might be avoided by a customized restriction of interactive parameter control and offer of information for the specific groups. Increasing the accessibility of GIS models seems necessary for a satisfying use of decision support tools by experts. This option might also support an even improved understanding of correlations between indicators and between prioritization of certain demands and resulting landscape changes.

The necessary investment of time for the users to understand and to control the tool as well as for processing the provided information turned out to be problematic. The required time might even increase with rising complexity of the interface and of the offered information content. The available time in the workshop was not sufficient to give the individual user the time he required. This experience reveals that the design of applications has to be developed in parallel with the tool to secure its meaningful implementation. Probably trade-offs must be taken into account due to a reduced complexity of the user interface depending on the respective application situation (workshop vs. self-exploration). Beyond user-related requirements we also discovered technical problems that have to be solved. Manual workflows for visualization are not feasible anymore if the amount of landscape change scenarios increases exponentially and if these scenarios can be defined interactively by the users. Furthermore, the degree of realism of the visualizations has to match the landscape development topic, e.g. vegetation types might have to be recognizable if the focus is on the ecological effects of agricultural management or landscape aesthetics. Hence, visualization workflows have to be redesigned to create sophisticated – and from the users expected – visualizations with a sufficient visual quality and appropriate level of detail in an automated way. In order to allow for analyses and visualization of output for any location on demand a generic, automated approach is necessary. This would ensure that the decision support platform is highly flexible and spatially independent.

Overall, it is hard to cover all aspects and demands and develop a useful user interface according to the ideas of different user groups. Particularly, it is challenging to satisfy all users. Generating a user interface that allows for adapting the amount of information, and thus its complexity, might be a constructive approach to meet the users' needs. Of great importance is an iterative approach for the development and testing of web-based platform system. Hence we aim at progressing by stages and with a particular focus on the interfaces to meaningful information provision in planning situations.

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Detailed information Appendix C:

Original title: Bringing ecosystem services indicators into spatial planning practice: Lessons from collaborative development of a web-based visualization platform

Authorship: Wissen Hayek, U.; Teich, M.; Klein, T.M.; Grêt-Regamey, A.

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Appendix C

Transdisciplinary process

Bringing ecosystem services indicators into spatial planning practice: Lessons from collaborative development of a web-based visualization platform

Abstract

Considerable efforts are made to integrate ecosystem services (ES) indicators into spatial planning practice. Although a lot of decision support systems already provide helpful functionalities, they are not yet integrated into everyday decision-making, mainly because they do not readily fit into planning processes in practice. There is an increasing awareness that the development should foster collaboration between interdisciplinary researchers and the end users of the tools to secure their suitability for such planning processes. Hence, user-oriented research and experimenting is seen as the appropriate approach for getting the tools ready for practice. Guidelines for conducting such processes are yet missing. Here, we contribute to the development of such guidelines by means of a practical case study. The focus is placed on how transdisciplinary (TD) research on spatial decision support systems should be designed for the integration of ES indicators into planning practice. In a TD project, a web-based visualization platform with indicators of relevant ES was developed to support municipalities of the Canton of Zurich, Switzerland, in assigning adequate watercourse corridors according to the revised Swiss Waters Protection Act. A preliminary as well as an enhanced version of the platform prototype were demonstrated to different actors for evaluating the platform's readiness for practice. We assessed the process design and the quality of the product in a discursive manner. Thereby, we implemented a set of assessment criteria derived from literature and adapted them to the case study at hand for the analysis of empirical material (participant lists, project schedule, meeting minutes and observation protocols). Finally, we discussed the lessons learned on developing significant ES indicators and their visualization and the conclusions drawn with respect to ensuring the quality of the platform development process. The results show that conceptualizing the ES indicators in strong collaboration with practice representatives increased their relevance to the actors' needs and therefore their legitimacy. Providing interfaces for collaboratively translating practical approaches into scientific models is, thus, crucial for the development of significant indicators. Furthermore, specifying the purpose of the visualization platform in planning processes requires prototyping and iterative conceptualization, because practice actors need concrete examples to express their specific demands. This also requires that the concept of developing the ES indicators and the spatial decision support systems should be treated rather as an

open working paper than as a final document agreed on in the first collaboration phase. Hence, time scheduling and occupying skilled project managers for this iterative process should be taken seriously.

1. Introduction

The growing attention of science and practice to ecosystem services (ES) has led to an increased interest in both the public and private sectors for approaches to develop and apply ES indicators in real-world decision-making (Daily et al., 2009; Ruckelshaus et al., 2013). ES are defined as goods and services provided by ecosystems, which contribute to human well-being, ranging from provisioning (e.g., food, fresh water) and regulating (e.g., water regulation) to cultural (e.g., recreational experiences) and supporting services (e.g., habitat for plant and animal species) (MA, 2005; de Groot et al., 2010). Several decision support systems are evolving for integrating ES into planning processes (Bagstad et al., 2013), i.e., interactive, computer-based tools, which help decision makers to visualize, compare, and consider trade-offs among many ecological, social, and economic values (Labiosa et al., 2013). Although a lot of these systems already provide helpful functionalities, they are not yet integrated into everyday decision-making, because they do not readily fit into existing planning processes (de Groot et al., 2010; Bagstad et al., 2013).

In order to transform current landscape patterns into more sustainable ones, the collaboration of science and a variety of public and private stakeholders is seen as key (Healey, 2007; Scholz, 2011; Steinitz, 2012). Thereby, the transfer of the relevant information to all stakeholders in a credible and comprehensible manner is the essential prerequisite for successful collaboration processes (Wissen et al., 2008). In participatory workshop settings, particularly GIS-based landscape visualizations have proved to be valuable communication and information media for different planning tasks (Salter et al., 2009; Schroth et al., 2011; Wissen Hayek, 2011). Furthermore, besides a sufficiently large set of GIS-tools that can support planning and design, GIS-tools are increasingly offered as participatory web platforms, and designing solutions is becoming more and more a rather collaborative effort than an expert task (Batty, 2013). Most recently, different frameworks and prototypes of web-based visualization platforms were presented which should facilitate the collaboration of heterogeneous stakeholder groups by providing information on possible impacts of certain demands for ES on the fulfillment of other demands (e.g., Klein et al., 2013; Grêt-Regamey et al., 2013). However, the development of such web-based platforms should not only foster the collaboration between GIS-modelers and interdisciplinary researchers but also with the end users of the tools to secure that the platforms actually provide helpful decision support for planning processes (Cook and Spray, 2012; Bagstad et al., 2013).

User-oriented research and experimenting is seen as the appropriate approach for getting the tools ready for practice (Daily et al.,2009). Yet, there are only few studies that assess the application of tools for quantifying biodiversity and ES in real-world decision-making and provide preliminary guidelines as basis for accelerating the development of effective tools (e.g. Ruckelshaus et al., 2013). Thereby, the quality of the system or platform development process is at least as important as the (technical) decision support system itself (Cash et al., 2003).

Approaches which are aiming at a co-production of practical outcomes that can be applied in a social or environmental context for problem solving, can be attributed to transdisciplinary (TD) research (Wickson et al., 2006; Pohl, 2008). However, the boundaries between applied and TD research types are gradual with regards to the distinguishing characteristics and the methodology (Hirsch Hadorn et al., 2006). There is neither a common definition nor methodology of TD research, but patterns of common characteristics can be identified (Jahn et al., 2012; Thompson Klein, 2013). According to Pohl (2005, 2011), important distinguishing characteristics of TD research are, that the researchers have to frame, analyze, and process a societal problem in a manner that (1) its complexity is grasped, (2) the diverse perspectives of science and society are addressed, and (3) that it links abstract and case-specific knowledge in order to (4) produce practically relevant knowledge according to the stakeholders' value systems. A collaboration of academic as well as non-academic stakeholders and a process of mutual learning are necessary to tackle the four issues (Wicksonet al., 2006; Pohl, 2005, 2011; Hirsch Hadorn et al., 2006). Since the process is characterized by science-practice collaboration and mutual learning, the usability of results of this process should be evaluated in a recurrent manner (Pohl, 2005; Hirsch Hadorn et al., 2006). Yet the development of guidelines for designing and evaluating TD research are still in its infancy (Carew and Wickson, 2010; Lang et al., 2012). Important sources for principles and concepts for design and quality evaluation of TD research processes and products are primarily case studies (Klein, 2008; Thompson Klein, 2013; Pohl, 2011; Seppelt et al., 2012; Stauffacher et al., 2012).

Here, we contribute to the development of guidelines by means of a practical case study. The focus is placed on designing and evaluating the TD research on a web-based visualization platform for the integration of ES into everyday decision-making. We analyze a TD process where the planning task of an ongoing collaborative planning process – the designation of watercourse corridors in the Canton of Zurich, Switzerland – was the starting point for collaborations between academic researchers and diverse actors from practice. The TD research aimed at the development of a web-based visualization platform for taking ES indicators of riparian areas and other indicators of socio-economic demands into account in the design of watercourse corridors at the local level. The intended purpose of the platform was to support discussion and balance diverse actors' conflicting interests in solution development. A preliminary as well as an enhanced version of a prototype were demonstrated to different actor groups for evaluation of the readiness of the platform for practice purposes. Here, we analyze empirical material of this case study, implementing a set of assessment criteria derived from literature. We discuss the lessons learned on how to develop significant ES indicators and to ensure the quality of the platform development process as well as the platform's decision support function in practice. We conclude by reflecting on requirements and implications of the development of spatial decision support systems integrating ES indicators into planning practice by implementing TD approaches.

2. Methods

2.1. Case study: Collaborative development of a web-based visualization platform

Riparian areas serve as habitat for plants and animals, as space for recreation and identification for the people, they provide freshwater and protect against floodwater or are economic production areas (Hauser et al., 2011). These services of the riparian areas contribute to human well-being (MEA, 2005). Since physical modification of rivers through human activities has degraded the provision of these services significantly all over the world, there are increasing political activities considering river rehabilitation (Gilvear et al., 2013). In Switzerland, about 42% of the watercourses do not provide the services sufficiently (Zeh Weissmann et al., 2009), and the recent revision of the Waters Protection Act (GSchG, 2014) from the 1st of January 2011 obligates the cantons, therefore, to define adequate corridors for watercourses. These corridors shall provide an area for enhancing or restoring the supply of the ES. The process of their designation should be characterized by an informed trade-off decision-making of different actors' economic, ecological, and social demands (Oberle, 2011). The Canton of Zurich started a collaborative process for the implementation of the Waters Protection Act. The goal of this broad-based participatory process was to define principles, approaches, and responsibilities for designating the watercourse corridors at municipality level. Furthermore, the canton wanted to provide the municipalities with spatial decision support tools. Particular tools were needed for effectively communicating and deliberating the spatial priorities of the provision of certain ES of riparian areas in practice for a spatially explicit definition of the adequate width of the corridor needed for watercourses. Therefore, ES indicators as well as other relevant indicators of the environmental, social, and economic dimensions (e.g., areas of high value for nature and landscape, restrictions of land use in watercourse corridors, or costs of revitalization measures) should be compiled and structured in form of a spatial visualization platform. In order to conceptualize and develop such a platform, the manager of the project "Implementation of the Waters Protection Act in the Canton of Zurich" of the responsible cantonal agency collaborated in a preliminary study with a university research unit, providing a background in landscape and environmental planning and GIS-based landscape visualization. Thereby, knowledge from scientific disciplines and from different professional fields was integrated to develop an actor-oriented solution, namely a web-based visualization platform providing the actors with relevant information for the negotiation process. Referring to Lang et al. (2012), the conducted project can be assigned to TD research, because it took up a problem from everyday life and applied a reflexive, integrative, method-driven scientific approach aiming at a solution for the problem of how to support the deliberative process of designating watercourse corridors effectively. The project had a duration of 19 months and was funded by the practice partner as well as by own resources of the science partner.

2.2. Assessing the process and product of platform development: The methodological approach

Due to the multidimensionality and context-specific nature of TD research, a universal method for its evaluation seems inappropriate (Klein, 2008). Instead, frameworks of generic principles and quality criteria for evaluation provide a basis for assembling coherent assessment criteria that suit the project setting and the research objectives of a concrete TD case study (Bergmann et al., 2005; Klein, 2008; Lang et al., 2012; Wickson et al., 2006). In the following, we state such generic principles, which we used for the evaluation of the TD research design on the web-based visualization platform. These principles were used to reflect on how to foster the integration of ES into everyday decision-making. In favor of a concise presentation of the analysis results, we selected the, in our view, most important principles concerning the research question in this paper: Implementing TD approaches, which are the requirements regarding the process design and the product of developing spatial decision support systems for integrating ES indicators into planning practice?

A major focus in TD research for the purpose of product and technology development is laid on the involvement of stakeholders in product development (Thompson Klein, 2013). With regard to sustainability indicator development, Rametsteiner et al. (2011) stress that the socio-political dimension of the process is as important as the technical development process, because the indicators are not only means to structure and communicate information but also the result of politically normative decisions on the relative importance of an issue. Hence, two aspects are of major relevance for the analysis of the process (Rametsteiner et al., 2011): (1) the diversity of participants and (2) the learning of actors with a focus on the problems and instruments related to dealing with the issues in question. The analysis should, thus, focus on how participants are selected, how they interact, and how decisions are made during the development of indicators as well as how learning of the participants is being enabled. Furthermore, the roles of the scientists and the other actors in the different phases of the development process should be made explicit in order to identify and specify their appropriate roles in such processes.

Table 11 – Assessment criteria for the process and product of the transdisciplinary research on a web-based visualization platform for integrating ecosystem services indicators into everyday decision making.

Theme	***Characteristics assessed***
1. Actors and their tasks/roles	Groups of actors and their tasks and roles in the project
2. Organization of the collaboration	Organizational structure and dynamic of the process development
3. Knowledge integration	Interaction of actors to integrate different types of knowledge
4. Practical relevance of the product	Credibility, saliency, and legitimacy of indicators and readiness of the visualization platform for its purpose in practice

Further, effective implementation of decision support systems that link knowledge to action require, in particular, active communication between the science and the practice communities, translation of information to improve mutual understanding, and active mediation of multiple stakeholders' conflicting views on how to achieve saliency (relevance to decision-making), legitimacy (information production is fair, unbiased, and respects divergent values), and credibility (the scientific adequacy of evidence and arguments are based on the methods and tools) of the TD research product (Cash et al., 2003). This integration of different types of knowledge, the problem- or product-oriented integration of knowledge, and the social integration of various actors with different interests, roles, and practices of communication constitute a major challenge in TD research (Jahn et al., 2012). Fostering communication and the integration of knowledge can be substantially influenced by the management and organization of the TD collaboration (Klein, 2008). In addition to the organizational structure of the interaction, also the dynamic of how the research process is developing should be taken into account, e.g., how the methodology is evolving over the course of the project in response to the feedback or changing perspectives of stakeholders (Wickson et al., 2006). An ideal TD process can be structured into a sequence of three phases: (1) problem framing and teambuilding, (2) co-creation of solution-oriented transferable knowledge, and (3) (re-)integrating and applying the produced knowledge in both scientific and societal practice (Lang et al., 2012). However, rather than following a linear course, the process often goes through a number of iteration loops of individual phases and the entire sequence. Hence, although the project chronology has proven helpful and transparent for evaluating projects, also a theme-oriented evaluation focusing on essential aspects of TD research projects can be useful for gaining a deeper understanding of the process and the steps toward knowledge integration (Bergmann et al., 2005).

Finally, TD research projects should conduct a reflection not only of the process, but also of the product (Wickson et al., 2006). Particularly the product's practical relevance should be assessed (Bergmann et al., 2005; Lang et al., 2012). Important quality criteria in the context of the case study were the credibility, saliency, and legitimacy of indicators and the usability of the web-based visualization platform.

Based on the principles discussed above, themes and correlating characteristics by which the case study was analyzed were defined as shown in Table 11. Diverse empirical material was analyzed including the project schedule, minutes, and participant lists from meetings of the scientists with different actors throughout the development process, interim and final documents of the concept of the visualization platform, preparatory documents of the demonstration of prototypes of the visualization platform, protocols of the feedback from potential user groups of the visualization platform, and protocols of observations during the prototype demonstrations. Additionally, the authors were personally involved in the process in a leading role and in the technical development of the visualization platform. They conducted participant observation and self-reflection during all stages of the development process.

The analysis was carried out in a discursive manner by the scientists who were involved in the project. The scientists analyzed the different themes first on their own and then discussed the individual results together and documented their insights.

3. Results: The process and product of platform development

3.1. Actors and their tasks/roles

Actors from science and practice collaborated in the development of the visualization platform. Following Bergmann et al. (2005), the participants from practice were divided into three groups – practice partners, practice representatives, and practice actors – which had different roles in the project (Table 12). Due to the overall project setup, i.e., that the pilot project was part of an on-going collaborative planning process (see Section 2.1), the participants in the development of the platform were already defined by the practice partner at the beginning of the project.

The first group comprised one practice partner, who was the head of a section of the Cantonal Agency of Hydraulic Engineering and Planning. He managed the major project "Implementation of the Waters Protection Act in the Canton of Zurich" and was the contracting body for the science partner. Thus, he was also in charge of contributing to and deciding on the overall direction of the pilot project "Platform Development", as it was part of his major project. Due to his decision, the participants of the major project were also participants in the sub-project, since they were already familiar with the task and the multiple conflicts of interests coming along with the designation of watercourse corridors.

The second group of participants from practice represented a group of actors with certain interests related to their professional field (e.g., interest in agricultural direct payments, nature protection, or protection of private real-estate property). The scientists collaborated directly with these practice representatives, who provided relevant information for the indicator development and visualization. Whereas in the first part of the project they were rather passively involved, limited to information provision, this group became an active partner in the second part. Practice representatives intensively collaborated with research scientists in the conceptualization and specification of ES indicator models.

The third group comprised the practice actors, which were involved in the evaluation of the visualization platform prototypes. They took part in the demonstration of the first and the second version of the prototype and had the opportunity to individually test it to provide their feedback on its assumed suitability for implementation in practice.

Research scientists with a background in landscape and environmental planning, GIS-based visualization, and graphic or web design were required for the technical development of the visualization platform. They were chosen when setting up the initial project concept. The role of the science partner was to manage the process of platform development and conduct its technical implementation.

3.2. Organization of the collaboration

Figure 32 presents the project chronology of the prototype development. The whole process can be divided into two major parts, the development of the first and of the second version of the prototype. Each of these parts comprises the three phases of TD research projects (problem framing and teambuilding, co-creation of knowledge, and application of results; see Section 2.2). However, whereas in part 1 the process showed rather chronological sequences of the phases, in the second part the phase of problem framing and team-building and the phase of co-creation of knowledge were mixed.

Table 12 – List of participating actor groups from science and practice with information on their scientific fields or professions in practice. The number of people (N) involved and the task or role of the respective actor group in the first and the second part of the project are given.

Scientific fields or professions in practice	***Part 1: Prototype Version 1***		***Part 2: Prototype Version 2***	
	N	Task/role in the project	N	Task/role in the project
Science Partners:		- Coordination of the project "Platform development" - Technical development - Contribution to the definition of the overall objective - Specification of platform contents and indicators		The same as in Part 1.
- GIS-/ Visualization Experts	3		3	
- Graphic/Web Designer	1		1	
Practice Partners who took part in the project by making their field of activity accessible as a pilot field:		- Coordination of the project ¨Implementation river protection act¨ - Contracting body - Contribution to the definition of the overall objective - Specification of platform contents and indicators		The same as in Part 1.
- Cantonal Agency of Hydraulic Engineering and Planning	1		1	
Practice Representatives, who took part in the research project on behalf of a group of actors:		- Providing information on relevant indicators - Providing current data - Providing feedback on the platform		- Providing information on relevant indicators - Specification of indicators - Providing current data - Providing expertise in setting up the logic of the indicator models - Providing feedback on the indicators - Providing feedback on the platform
- Cantonal Agency of Hydraulic Engineering and Planning	4		4	
- Planners of pilot municipalities	1		1	
- Consultant for cultural heritage protection and urban planning	1			
- Cantonal Agency of Agriculture			1	
- Cantonal Agency of Nature Protection			1	
- Consultant for the agricultural direct payment system			1	
Practice Actors who are potential end users of the product, but who were not directly involved in the development:		- Participation in the advisory board meeting, in which the first version of the prototype was demonstrated - Feedback on the usability of the prototype for communicating and trade-off decision-making in the designation of watercourse corridors - Suggestions for enhancement with regard to indicators and alternative designs of watercourse corridors in order to meet the practical requirements		- Participation in the expert meeting in which the second version of the prototype was demonstrated - Feedback on the usability and potential for implementation of the prototype, especially in the Cantonal Agency of Hydraulic Engineering and Planning for communicating and trade-off decision making in the designation of watercourse corridors - Suggestions for enhancement with regard to indicators and alternative designs of watercourse corridors in order to meet the practical requirements
- Representatives of cantonal agencies: Hydraulic Engineering and Planning; Legal Service; Real Estate Office; Spatial Planning; Cultural Heritage Protection; Agriculture; Nature Protection; Soil Protection	26		10	
- Planners and representatives of four pilot municipalities	17		1	
- Banking sector and insurance	1			
- Energy companies	2			
- Fisheries Association (Canton Zurich)	2			
- Municipalities (Association of Public Servants and Administrators and the Association of City Councilors of the Canton of Zurich)	2			
- Landlords Association Zurich	2			
- Environmental protection and nature conservation associations	9			
- Forestry Business Association of the Canton of Zurich	3			
- Association of Farmers of Zurich	3			
- Regional Planning Organization of Zurich	11			

In the first part, the active collaboration took place primarily between the science and the practice partner. Major milestones were agreed concepts of the platform's contents and its application, which were suggested by the science partner. The practice partner criticized the suggestions, and this feedback was used for further concept adaptation by the science partner. Practice representatives were only involved in the project in form of delivering GIS data and information required for calculating the indicators agreed on. Further, in a pretest of the platform demonstration they were asked to consult with regard to setting up the program for the application of the prototype. Practice representatives and practice actors were then invited to the demonstration to give feedback on the platform's suitability for practice. Additionally, they received the link to the online platform for individual exploration and further feedback provision.

In the second part, first, the project concept was revised collaboratively by the science and the practice partner, based on the feedback of the practice representatives and practice actors gathered on the prototype version 1. However, this time the concept was treated as a working document, because it was agreed that the required platform contents and indicator specifications had to evolve from the collaboration of the science partners with the practice partner and the practice representatives of relevant professional fields (e.g., agriculture and nature protection). Thus, new teams had to be built, and the co-creation of knowledge was characterized by several meetings and discussions by phone and e-mail between science and practice representatives, leading to a common specification of the GIS-models for indicator calculation. In the course of this process, the concept of the platform was iteratively revised and adapted. The final concept of the platform's content, functionality, and methods for indicator calculation were only available at the end of the pilot project. The second version of the prototype was again demonstrated to the practice partner, representatives, and actors, who also after this event could individually test the prototype for a longer period. Their feedback was again used for a reflection on the usability of the prototype in practice.

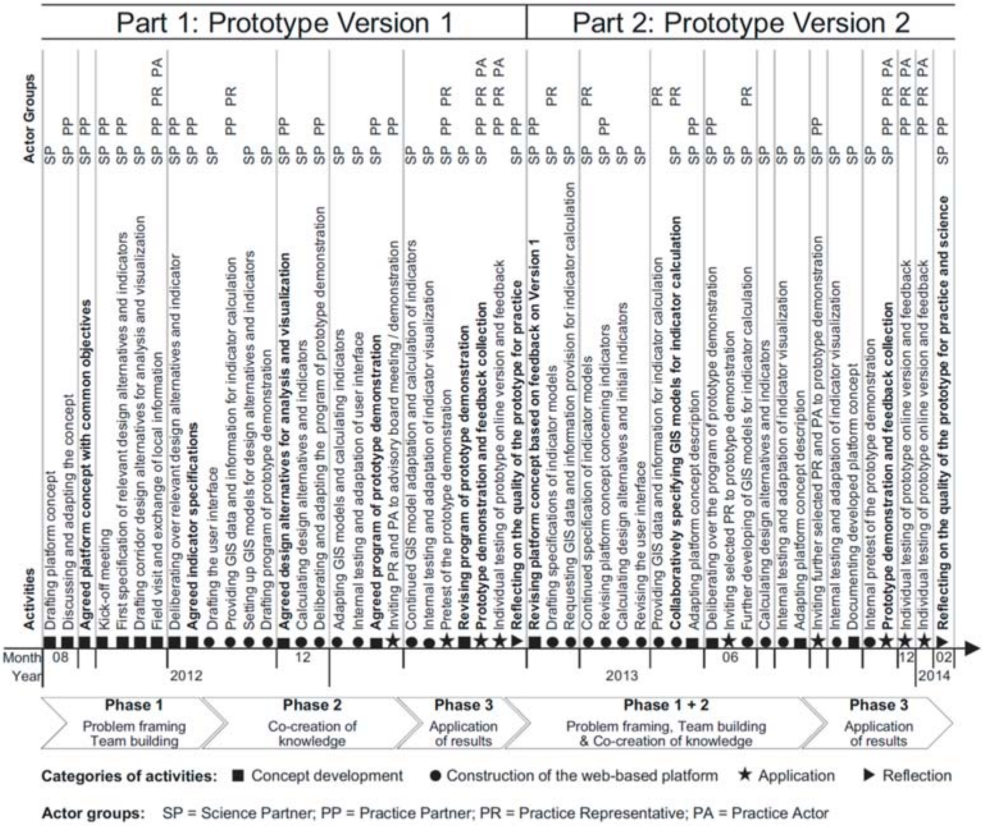

Figure 32 - Chronology of the procedure of conceptualizing, developing, applying, and revising the two prototypes of the web-based visualization platform. Activities in bold were major milestones of the prototype development. The phases 1–3 are typical of a transdisciplinary research process (see Lang et al., 2012).

3.3. Knowledge integration

The integration of knowledge from the participating scientific and practice fields was driven by the orientation on the product. The science partners contributed their knowledge and technical skills to modeling spatial indicators and visualizing the results with a web-based platform. They particularly took care that for the calculation of the design alternatives of the watercourse corridors and of the indicators generic GIS-models were set up, which can be applied with the cantonal GIS-data generally available to all municipalities in the Canton of Zurich. In the first part of the project, they also provided knowledge on specific ES indicators, such

Current situation:
No watercourse corridor

Design alternative 1:
Designation of watercourse corridor according to the flood water protection area

Design alternative 2:
Watercourse corridor is reduced to a minimum in the city center so that buildings are not included in the corridor

Figure 33 - Indicator maps of the provision of the recreational service of public green spaces for the current situation and alternative watercourse corridor designs: Degree of supply of employees with public open space within a walking distance of 200 m (intense green = 100% ≥ 5 m_2/employee). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

as the degree of supply of people with public green space indicating the watercourse corridor's potential provision of recreational services. However, the model for indicator calculation was based on an existing method developed by the City of Zurich (Stadt Zürich, 2014).

All other contents, such as the design alternatives of watercourse corridors according to specific criteria, the prioritization of areas for river revitalization, or costs of revitalization, were defined by the practice partner and practice representatives. In addition, they provided the empirical knowledge on the practice procedures and the target knowledge on the purpose for implementation, which guided the science partners in preparing customized sets of information in the visualization platform. For example, for the urban pilot municipality "Dietikon" (prototype version 1) basic data of the municipality's status quo (e.g., density of the built-up area and the indicator on the provision of the recreational service) was assembled with possible alternative designs of the watercourse corridors and indicators on the resulting costs, buildings in the corridors affected by certain restrictions, and the effect of the corridors on the recreational service. The design alternatives were basically defined by specifications of the Swiss Waters Protection Ordinance (GSchV,2014). Additionally, the pilot municipality was encouraged to adapt these alternatives to the local conditions in order to reduce conflicts between different actors' demands. During the demonstration of the first prototype, the practice actors learned about the potentials to implement the visualization platform into the procedure of designating the watercourse corridors. For example, the ES indicator regarding recreational service showed that employees in the city center of Dietikon are currently insufficiently served with public green space (Figure 33).

A watercourse corridor design alternative, which is based on the floodwater protection curve according to the Swiss Waters Protection Ordinance (GSchV, 2014), would not only serve the purpose of floodwater retention, but also recreational purposes along the river. In case of good green space design, these areas could provide multifunctional and attractive green spaces, significantly enhancing the current recreational situation. Since the city center is densely built, however, this design alternative causes a conflict with the owners of real-estate situated within this watercourse corridor, who are, hence, facing restrictions placed on property use. The ES indicator shows the impact on the recreational service in case of another design alternative, where the watercourse corridor is reduced to a minimum so that the buildings are excluded from the corridor. In order to support individual exploration of the online-platform, a tutorial with descriptions of the indicators and examples of the insights they can provide was made available for download. The practice actors' feedback on the first prototype, which was based on their knowledge of existing practices and the information required, was a qualified check of the platform's fitness for purpose.

In the second part, the further development of the prototype focused on significant indicators for the agricultural pilot municipality "Marthalen". The most important information for the target group of end users, the farmers, were indicators of the impacts of alternative watercourse corridor designs on agricultural management, in particular, the impact on the cultivated land of high quality and the ecosystem's provisioning service measured in terms of the farmer's income. For the latter information, the practice representatives regarded a generic indicator, suggested by the science partner, as insufficient for the practical purpose of negotiating different services of the watercourse corridor and trade-off decision-making. Instead, an indicator that shows the compensation for services provided by the farmers for improving the landscape structures and ensuring the appropriate use and care of the watercourse corridors should be developed. These compensations, called direct payments, constitute a key element in Swiss agricultural policy (Federal Office for Agriculture, 2015). Two practitioners, one of the Cantonal Agency of Agriculture and one of a non-governmental organization consulting the federal administration on agriculture as well as farmers, which were both experts on direct payments, collaborated intensively with the science partners. In this way, the target knowledge of the practice representatives was integrated into the scientific models. The indicators take actual incomes generated on the land parcels in the case study area as basis. Further, they take into account the current and also the possible future agricultural direct payment scheme, which was still under discussion. Hence, the indicators can address questions which the farmers actually have, namely, the impact of watercourse

Figure 34 - Visualization of the ES indicator of agricultural production measured as marginal income per agricultural parcel per year. The darker grey the parcel, the higher the marginal income. Clicking with the mouse on a specific parcel, the quantitative information on the marginal income appears.

corridors on the current income and on the potential future income if the proposed new direct payment scheme would be enacted (Figure 34 and Figure 35). The science and practice partners mutually decided to prepare indicators of the ES service of habitat provision and of cultural services also in monetary terms. The habitat provision can be increased in the agricultural area with larger areas of extensive management. Since the farmers get direct payments for extensive management, the same indicator models for the production service was applied. The cultural service was expressed in terms of the willingness of an adult inhabitant to pay for the revitalization as an additional benefit for his recreation. The amount of money was based on results of a study conducted in Switzerland (Arnold et al., 2009). The assumptions and decisions made by the participants actively involved in specifying the contents and indicators of the platform were documented to make the approach of knowledge integration transparent. This document was made available for download on the online platform.

3.4. Practical relevance of the tool

Concerning the first version of the prototype, there were rather diverging opinions on its quality. Some practice actors evaluated the possibilities of the visualization platform as good, whereas others

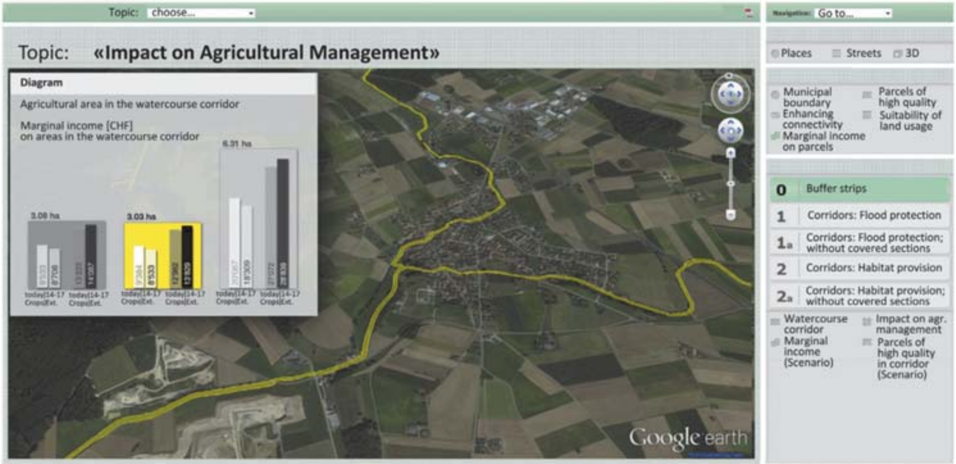

Figure 35 - Information and indicators provided for analyzing effects of watercourse corridor designs on the agricultural production service as monetary benefit for farmers. Spatial visualization of the extent of the corridor according to the flood water protection curve (yellow area) and diagram with correlating quantitative indicators on the total agricultural parcel area located in this corridor as well as the marginal income produced on this area for an ordinary crop sequence and for an extensive management according to the current and potential future agricultural direct payment scheme. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were more skeptical, particularly with regard to the significance of the ES indicators. These critical actors were primarily experts, who criticized that their knowledge was not sufficiently integrated into the selection of relevant indicators and the specification of models to calculate them. For example, the indicator map on the provision of the recreational services was appreciated with differing degrees of added value by experts of heterogeneous fields. For some the indicator provided helpful information for a first appraisal of the watercourse corridors' effects, for others the indicator was far too generic. The actors recommended enhancing the definition of the target group and thus the purpose of the information and the indicators. The platform, for instance, should be either enhanced to support specific analysis tasks of the administrations at cantonal and/or municipality level or it should be prepared to preliminary suit communication with heterogeneous actors affected by the designition of watercourse corridors.

In contrast to the first version, the second version of the prototype was said to provide a good basis for discussion. For example, actors mentioned that the platform could support deliberation on concrete revitalization projects by illustrating synergies between ES, socioeconomic benefits, and river protection. They were of the opinion that the platform could communicate these synergies effectively.

They thought that this could, in turn, facilitate the understanding of different actors' demands and potentially increase the societal acceptance of certain watercourse corridor designs. In this way, the platform could possibly mitigate the political negotiation process on the designation of watercourse corridors. However, practice actors pointed out that the platform could only serve as an overview but not as a consulting tool, e.g., for individual farms and their business plans. Further, the information provided was regarded as not sufficiently comprehensive to support the concrete designation of watercourse corridors. The resulting platform prototype was classified as a hybrid providing an expert level for individual information exploration and a presentation level for communicating major findings to stakeholders. However, none of the levels was regarded as sufficient for the respective purpose. Therefore, the actors recommended to further customize the platform with regard to its purpose, which also required further specification.

4. Discussion

We presented the TD case study on the collaborative development of a web-based visualization platform to discuss the lessons learned on integrating significant ES indicators into decision support systems that are actually useful for planning practice. First, we identified the role of different actors or actor groups as an important aspect in this context. The overall process management led by the science partner with regard to the scheduling of tasks has proven to work well. However, due to the dynamic development of the overall process in the second part of the project, more personal resources for project management than originally planned had to be made available. Further, the strong collaboration of science and practice partners in directing the definition of the content of the visualization platform was effective, because both partners always supported the chosen approach and the resulting prototypes. This created a positive attitude to the development of the platform and the openness to try out different strategies and approaches. Thereby, the group of practice representatives had a crucial role in the definition and specification of ES indicators and respective GIS-models. However, the collaboration between them and the science partners was temporarily difficult, due to delayed delivery of necessary data. The commitment to collaborate is an important prerequisite for successful processes of ES indicator development, which should be obtained as early as possible.

A second insight is that the linear process of concept development, implementation, and application did not lead to desired results in terms of relevant and legitimate ES indicators. In contrast, the iterative definition and specification of ES indicators in the second part of the project was more successful in generating models and visualizations of the results meaningful for practice actors. The importance of an iterative science-policy process is a lesson that also Ruckelshaus et al. (2013) learned from their evaluation of case studies. In our case, this iterative and interactive approach was made possible by the decision to work with an open concept of the platform's contents. However, the open concept did not mean that there was no concept of the indicator and platform development. A draft conceptual framework should serve as a central reference point for the process of further adaptation and revision. Furthermore, documenting these steps throughout the process provided transparency of the whole approach for all actors and further stakeholders not involved in the collaboration. The possibility to read about the assumptions and decisions made can increase the credibility and legitimacy of the ES indicators for practice actors.

During the different phases of the project, varying types of communication were applied for integrating knowledge about planning purposes and practices as well as required information into the scientific specification of the ES indicators and the design of the visualization platform. These types of communication can be distinguished with regard to the flow of information and commitment of science and practice partners (Trutnevyte and Stauffacher, 2012). The communication with the actors from practice ranged from provision of information only to actual collaboration with two-way communication on the conceptualization and specification of indicator models. The latter type of communication was most effective in terms of knowledge integration. In particular, the ES indicator on agricultural production was valued by the practice actors as salient and legitimate indicator. Hence, the expertise of participants representing a group of actors should be regarded as key factor for conceptualizing and implementing ES indicators into practice. Rather than involving all of the participating actors with high intensity, a targeted collaboration with different actor groups applying involvement techniques as appropriate, a so-called functional-dynamic organization (Stauffacher et al., 2012), seems to be more suitable.

Due to the mutual definition of indicators, criteria of both science and practice were taken into account to generate the GIS-models for calculating the indicators. This also ensures credibility for all collaboration partners (Cash et al., 2003). However, in our case study, the purpose of the visualization platform was not defined sufficiently precisely until the end of the project. This in turn rendered the definition of relevant indicators even more difficult. In particular, more effective methods are needed for integrating target knowledge on the purpose of ES indicators and decision support systems in practice. For example, the testing of prototypes in actual planning settings in pilot projects could be useful to this end.

Another finding is that the learning process the actors go through is an important component of making ES indicators and their visualization fit for the practice purpose. In the beginning of the project, the practice actors were not able to clearly define their requirements and expectations. For this reason, the purpose of the ES indicators and the target group of the visualization platform were defined rather broadly. With each of the prototypes it became clearer which purposes the visualization platform might probably be helpful for. The prototypes turned out as effective media for successively defining the contents and the functionality of the visualization platform including ES indicators. Bearing in mind that a learning process is required to specify the expected product, it should be iteratively asked throughout the collaboration process and based on concrete indicator examples, what the purpose of the ES indicators is in practice.

Finally, the method for analyzing this case study, based on principles for TD research design and evaluation, supported a structured and systematic discourse. This actually fostered a deeper insight into the process of the ES indicator development in the case study. We recommend taking into account the available principles for TD research not only for the evaluation of TD research projects but also especially for setting up collaborative projects of science and practice partners to secure the quality of the process and its products. Correctly designing the collaboration process is one prerequisite to successfully integrate ES indicators into everyday decision-making. Integrating phases for reflection of the overall process and the quality of the products, as demonstrated in this paper, is therefore very important to enhance our understanding of what effective ES indicators and decision support systems for practice purposes are.

5. Conclusions

Our findings have very practical implications for the integration of ES indicators into spatial decision support systems implementing TD approaches. We experienced that when the platform and its ES indicators advanced and the knowledge and understanding of possibilities for information provision increased, the demands of different actors became more concrete and initial ideas could change. Prototyping is, thus, seen as a useful approach, which enables to specify the purpose with practice actors in an iterative manner. In our case, this provided a good basis for a follow-up project, which aims at developing the actual visualization platform of watercourse corridors and relevant indicators of their impact as part of a decision support system for practice. Moreover, the provision of interfaces for the collaborative translation of practical approaches into scientific GIS-models is crucial for the development of significant ES indicators. The commitment of practice representatives to collaborate actively and an open concept that allows trying out different approaches were identified as important prerequisites. The concept of developing the ES indicators and the decision support systems should be treated rather as an open working paper than as a final document. Hence, scheduling of time and occupying project managers with adequate knowledge and management skills for the iterative communication and specification process should be taken seriously.

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Detailed information Appendix D:

Original title: Do New Urban Densities Provide Urban Landscape Identity? A Concept for Operationalizing Qualitative Factors Combining Sophisticated Visualization Workflows

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Appendix D

Sophisticated visualization workflows

Do new urban densities provide urban landscape identity? A concept for operationalizing qualitative factors combining sophisticated visualization workflows

Abstract

Continuing pressure on urban areas due to growing population and further urbanization affects urban quality. Many cities and agglomerations try to cope with negative effects of urban sprawl by further densification of existing built-up areas. As a consequence, green and open spaces are disappearing. Among other ecological and socio-economic urban qualities, this is affecting the sense of a place and place attachment of the local inhabitants. However, there are no indicators available, which allow in planning processes for an effective assessment of the impact of further densification on the urban landscape's identity. One challenge is that assessing the impact on the landscape's identity requires both objective and subjective approaches. Objective approaches are well established, for example, in environmental impact assessments untypical elements of a landscape contributing to a loss in landscape aesthetics and character are evaluated. However, these approaches are rather applicable on the rural than on the urban landscape. Furthermore, subjective approaches still lack of suitable tools for integrating individual perceptions of stakeholders into the evaluation process. In this paper we present an approach based on GIS- and rule-based interactive modeling and visualization tools, which allows for objective and subjective assessment of the urban landscape's identity in participatory planning processes. For the case study of Schlieren, an agglomeration of the city of Zurich (Switzerland), we show exemplarily the implementation of this approach. Combined assessment of hard and soft factors of urban green and open spaces contributing to the urban landscape's identity provides a powerful tool to identify local thresholds of urban densification, and thus proactive planning of sustainable urban development taking into account the residents' requirements directly.

1. Introduction

In Switzerland, official settlement development concepts focus on a higher utilization of built-up areas (Bundesamt für Raumentwicklung ARE, 2009). The main goal of this strategy is to contain urban sprawl (Gennaio et al., 2009) by increasing densities in existing built-up areas of cities and agglomerations. There are evident benefits of planned densification, e.g., support of regional thinking and controlling, setup of priorities, development of economy, sustainable and optimized transportation connections (Bundesamt für Raumentwicklung ARE, 2009). However, urban densification may also entail threats to urban quality.

An important factor of urban quality is the sense of place and the people's place attachment, defined as "the positive emotional bonds that develop between individuals and their environment" (Brown and Raymond 2007, p.89). Changing urban environment – e.g. due to increasing floor area ratios in land use plans – can have an impact on the people's place attachment. Thresholds with regard to this aspect are not yet known. Existing planning instruments for securing spatial identity are predominantly based on objective indicators. These comprise, for example, the amount of recreation offers or the connectivity of foot and bike paths in or next to the settlement areas (Bundesamt für Raumentwicklung ARE, 2003). More recent approaches stress the relationship between social aspects of urban densification and the people's identity with their area (Bundesamt für Raumentwicklung, 2011). The significance of relationships between soft and hard factors are too important to be disregarded (Soini et al., 2012).

For solving most of the challenges in future urbanization, spatial knowledge of both urban and spatial planning and stakeholders are required (Taubenböck and Esch, 2011). The emphases of individual and emotional (soft factors) compared to physical (hard factors) indicators are still unknown so that they are not yet taken into account in urban planning processes comprehensively. Moreover, subjective perception contributes to individual place identity (Soini et al., 2012). In order to achieve an urban densification, which is accepted by the people and is identity generating, the subjective perception has to be integrated into the assessment of urban densification proposals.

We present the framework for preparing 3D visualizations linked to objective indicators that offers suitable means for assessing both the soft and hard indicators for the quality of urban densification. First, a literature review is given on the theory of landscape perception and indicators to measure a landscape's potential to generate identity. Then, a case study area in a suburban region in Switzerland, the community of Schlieren, is presented. In the methods section, the framework is described and results of preliminary 3D visualizations linked with objective indicators are given. These are discussed with regard to their suitability and further development possibilities for future application as assessment instruments.

2. Theoretical frame

2.1. Landscape perception

As Rodewald (2011) describes, there is a three-component view of a place (Figure 36). The first component is evolution based and allows for »reading« the landscape. This view supports orientating oneself and gathering information on a situation in a landscape. The second view component is for receiving colors and aesthetical stimuli. Through this a place gets its

Figure 36 - Illustration of the three component view of landscape perception.

characteristic appearance. The third component of our viewing is linked with individual cognitions. A symbolization and identification gives any place a special importance, which depends on preferences, values, preconceived imaginations and individual signs. This third component converts a place to an emotional place, which gets a personal recognition value. Such a sensual, informative and associative view generates the sense of a place.

Girot and Wolf (2010) describe the three components as analytical, physical and poetical view. The analytical view measures the spatial composition and builds relationships between objects. The physical one is described as a corporal experience of cognition. The individual touch is here given by the poetical component, which combines the viewing results to something new and gives them a distinctive attribute for dealing with compositions in landscape. Such subjective parameters should be considered to guarantee comprehensive planning for sustainable urban developments. This requires making aesthetical effects of future developments measurable and visible (Meijer et al., 2011).

2.2. Indicators for a landscape's potential to establish identity

In practice and research, visual impacts are indicated by observers' expressions of preference or judgments/ratings of visual aesthetic quality, which include scenic quality, visual quality and scenic beauty as well (Daniel & Meitner, 2001). These preferences are not yet linked with more comprehensive tools, which allow for analyzing both the sense of a place and other factors of urban quality, e.g. urban density, costs for green space infrastructure, energy efficiency and others. Providing tools for subjective and objective assessment, which allow a weighting of different indicators, could support trade-off decision making and the identification of thresholds for aesthetical aspects.

The concept of ecosystem services (ES) offers a vast systematic framework for goods and services to humanity. The ES can be categorized into provisioning services (e.g. wild foods, crops, fresh water and plant-derived medicines), regulating services (e.g. filtration of pollutants by wetlands, climate regulation through carbon storage and water cycling, pollination and protection from disasters), supporting services (e.g. soil formation, photosynthesis and nutrient cycling) and cultural services (TEEB, 2010). The latter comprise landscape and place identity as well as spiritual and aesthetical services (de Groot et al., 2010). The principal of valuing ecological landscape components by ES allows a new approach to quantify and bring landscape in comprehensible indicators for enabling a trade-off of several socio-economic values (Grêt-Regamey et al., 2012; Grêt-Regamey et al., 2008).

In urban areas, the ecosystems services depend on the quality of the following major ecosystems: street trees, lawns/parks, urban forests, cultivated land, wetlands, lakes/sea, and streams. Services provided by these ecosystems are, for example: air filtration, micro climate regulation, noise reduction, rainwater drainage, sewage treatment, and recreational and cultural values (Bolund and Hunhammar, 1999). In fact, ecosystem services provided by urban green space patterns can provide healthy environments and physical as well as psychological health benefits to the people residing within them. A healthy environment can also contribute an improvement of socio-economic benefits (Tzoulas et al., 2007). The number or area of culturally important landscape features or species support the service of providing signs of cultural heritage and identity (de Groot et al., 2010). Since land use management affects the provision of mainly regulating and cultural ecosystem services (van Oudenhoven et al., 2012), it is very important to develop suitable approaches for integrating the assessment of the impact of landscape changes on the identity into urban planning.

3. Case study area

The 3D urban model is developed for the case study area Limmattal (valley of the river Limmat), an agglomeration in the northwest of Zurich (Figure 37). Special focus will be laid on a dwelling zone in the community of Schlieren. It comprises an area of about 6,38 km² and a population of 16’100 (about 2’462 inhabitants/km²) (Statistisches Amt des Kantons Zürich, 2010). Schlieren is a Swiss city in the agglomeration of Zurich. It combines residential areas, industry and, at the river Limmat, important recreational area for the core center of Zurich city in tight space. Since the 1960s the population increased rapidly up to 10.000 inhabitants (Statistisches Amt des Kantons Zürich, 2010) due to relocation of industry to the

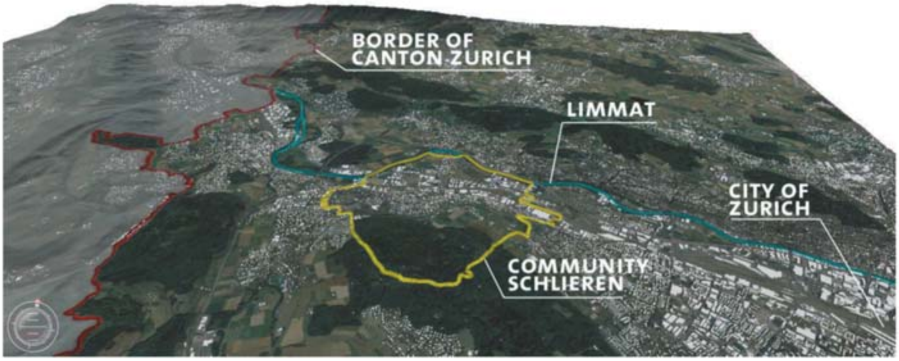

Figure 37 - Overview of the community of Schlieren (yellow line) situated in the valley of the river Limmat. Red line marks the border of Canton Zurich with the city of Zurich in the lower right corner of the figure.

agglomerations and good traffic connections to Zurich. Today, it has an important role as transit area and as arising living space for a heterogeneous population. Currently, Schlieren has an annual growth of 800 people and an increase of 4’000 inhabitants was registered for the last seven years. The problem of such a moving in is that living space for only 2’500 people is in planning (Vögli, 2012). Thus, this focus area is ideal for analyzing different possible future situations and development strategies in order to cope with the development pressure.

4. Methods

A participatory approach is necessary for detecting accepted thresholds of densification in dwelling zones taking into account place attachment (de Groot et al., 2010). 3D visualizations of the urban landscape offer high potentials to effectively support such participatory processes (Xu and Coors, 2012). New and innovative steps in data acquisition and mapping offer a flexible back-end for land use modeling and 3D visualization (Grêt-Regamey and Wissen Hayek, 2010). An interactive approach might be important for a high rate of return and variety of indicator information from the participants (Belton and Elder, 1994; Bruigat and Chittaro, 2008; van Schaik, 2010).

Taking into account these requirements, we set up an interactive collaborative modeling and visualization platform linked with objective indicators of identity and urban density. The preliminary platform was tested with stakeholders with regard to its suitability for participative assessment. The final platform shall be suitable for identifying trade-offs and thresholds associated to urban densification scenarios and place identity. In the following, the major components of this platform (data acquisition and mapping, procedural 3D visualization, participative assessment) are described (Figure 38).

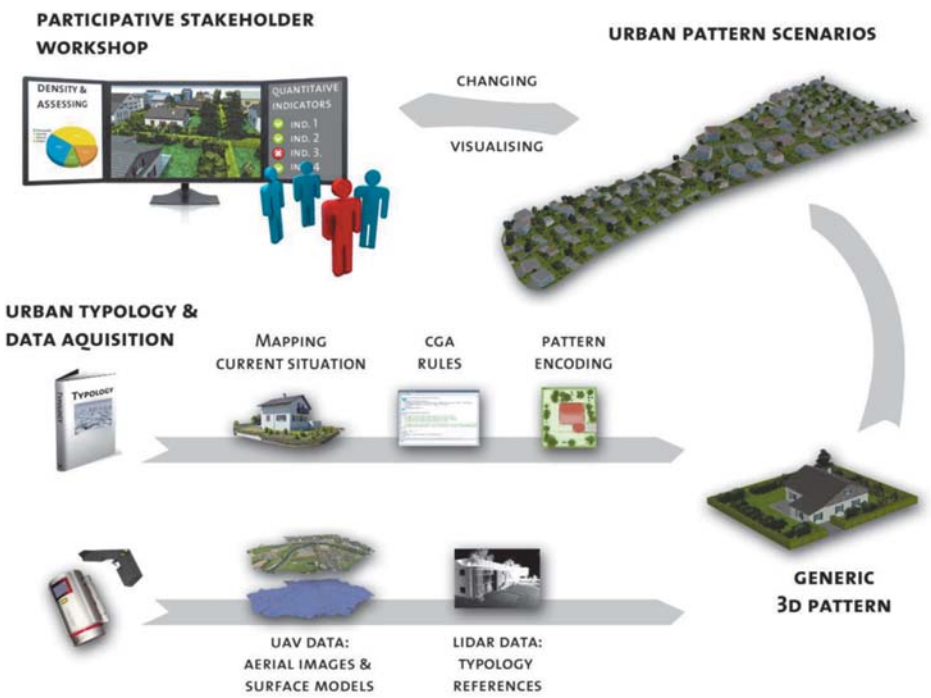

Figure 38 - Framework demonstrating the strings of data acquisition and 3D pattern generation suitable for interactive scenario visualization in participative stakeholder workshops or interactive choice experiments.

4.1. Data acquisition & mapping

On the one hand, modeling approaches are necessary in order to assess and communicate consequences of complex urban system scenarios and calculate meaningful indicators. On the other hand, realistic 3D visualization with a high level of detail is necessary to assess effects of landscape change scenarios on the landscape view and the people's landscape perception (cf. Wergles and Muhar, 2009). For these reasons, we focused on highly accurate data acquisition methods for accurate modeling and realistic 3D visualizations. To this end, modeling and 3D visualization is based on two methods of data acquisition. We generate high accurate and up to date elevation models and aerial images by implementing (1) a terrestrial laser scanner (TLS) (Riegl VZ-1000) and (2) an unmanned aerial vehicle (UAV). (1) A terrestrial laser scanner scans with a horizontal and vertical moving laser beam over the landscape. Through detection of the back-reflected laser beam from objects, the distance to these target points can be calculated by time-distance method. The device registers in this way point clouds of landscape objects, which are hit by laser. Depending on the defined scan resolution (moving

Figure 39 - Processed high resolution digital surface model (DSM) with aerial image texture of an Unmanned Aerial Vehicle (UAV). The data shows a part of the case study area of Schlieren (Canton Zurich, Switzerland) and has an accuracy of 8 centimeters (DSM and aerial image).

speed of laser beam on horizontal and vertical axes) a dense point cloud is created, in which each single point has its own geo-referenced xyz coordinate through GPS localization of the scanner position itself. With a mounted camera on top the point cloud can be colorized by the RGB values of the photos (Lemmens, 2011). (2) The unmanned aerial vehicle consists of a modified camera, GPS autopilot and radio module. Linked with a ground-based notebook, the fly path for the airframe is defined. The UAV flies autonomously by defined waypoints and heights over the terrain and takes images. Through exact trigger-coordinates and attitude of the images by GPS-autopilot and inclination sensors, an afterwards auto-processing of control points is possible to generate geo referenced surface models and aerial images (Figure 39), (Manyoky et al., 2011).

Both data pools are complementary, which simplifies the acquisition and modeling parts. Aerial images are used for GIS data processing (aerial images, digital surface/elevation model) as well as for typology mapping next to field work. Point cloud data gathered from terrestrial laser scanning is used for generating elevation models and for generating 3D building objects (direct implementation of architecture details by manual and automatic modeling tools). Particular strength of these acquisition methods is that they offer a new level of detail and spatial coverage in up-to-date basic data.

4.2. Procedural 3D visualizations

3D visualizations have been proved to be supportive tools for participatory landscape planning workshops (Pettit et al.,

Figure 40 - Colorized point cloud from terrestrial laser scanning (left), static 3D building object model based on point clouds (mid), example of a building type generated in the CityEngine system implementing CGA shape grammar rules (right).

2011; Wissen Hayek, 2011). For 3D visualization of urban densification scenarios, we implement a procedural urban modeling approach using CGA shape grammar implemented in ESRI's CityEngine system (www.esri.com/cityengine). The software can quickly visualize urban environments including green spaces in interactive three-dimensional views with a high level of detail (Neuenschwander et al., 2011; Wissen Hayek et al., 2010) enabling for evaluation of alternatives and iterative design workflows (Halatsch et al., 2008; Ulmer et al., 2007).

In field mapped building types (e.g. single-family houses, multi-family houses) are encoded as CGA rules. Combining rules for building types leads to rule sets for urban patterns, in our case a dwelling zone. The density aspects are integrated in those rule sets. Executing these rules, 3D urban patterns are generated. Rule parameters can be changed interactively, which allows for iteratively assessing alternatives in real-time to detect the trade-offs between urban densification and place identity. These quantitative parameters offer stakeholders the possibility to check the basic assumptions of the scenarios and thus can contribute to the transparency of the visualization model. Through a live reporting option of quantitative indicators in ESRI's CityEngine system, iterative analyses based on objective indicators are possible. In our preliminary model, we calculated floor area ratios, population densities, population of dwelling zone, green space, green space maintenance costs, potential habitat population, infrastructure costs, for an indicator-based comparison of scenarios.

Newer features in ESRI's CityEngine support import of geo-located Google Warehouse buildings (http://sketchup.com). However, 3D object models can also be generated from the TLS and UAV data. The data can be easily prepared and processed to get high detailed 3D objects and ground data. This workflow is useful for modeling static non-CGA based buildings, which won't be influenced in scenarios and support the stakeholders' in orienting themselves and thus contribute to the suitability of the model for assessing place identity (Figure 40).

Furthermore, there is high potential to automate CGA rule processing and reconstruct buildings by detection tools (Mathias et al., 2011; Becker, 2011). This automatic detection method offers new flexibility in generating a larger set of CGA building rules for more detailed scenarios with realistic appearance. In this way, rules can be automatically detected out of real architectonic patterns. With an integration of such detection technologies in the data acquisition workflow, the creation of present conditions in CGA would highly reduce manual visualization work. The scenario setups would base on detected CGA grammar out of real field data by modifying rule parameters.

4.3. Design of a participative assessment of place identity implementing the tools

Expectations with regard to the landscape scenery differ between heterogeneous population groups (Soini et al., 2012). To this end, participation of a broad population should be aimed at, to collect these various individual opinions and conceptions about threshold values of landscape components concerning place identity. In combination with the interactive modeling approach, online surveys can facilitate an extensive participation. Van Schaik (2010) has shown that interactive 3D visualization for public consultation has a broad acceptance – also of older people – and that it can be offered also in a "survey mode" with backchannel for user comments, questions, preferences and critics for a qualitative data collection.

Technical options increase the quality of feedback (quantitative and qualitative data) on thresholds and trade-offs. The possibilities of NVidia's RealityServer (www.mentalimages.com) supports CityEngine models in interactive and photorealistic web-application and low system resources (e.g. mobile devices) through cloud computing. This setup can bring the CityEngine models as interactive experiments online. Thus, all interviewees can define their own thresholds and supply a high return-rate and extensive data of individual trade-off decisions.

4.4. Pre-test design

We conducted a pre-test for assessing preliminary results of implementing the presented framework focusing on the interactive procedural 3D visualization with linked objective indicators. The pre-test was set as interview with the goal to identify the critical steps and technical issues in participative application of the tool and get also first comments and critics of potential users. It was not set up as representative study. Five experts were interviewed to get information on their impressions of the model. The interview was divided in three stages: introduction, presentation and interview. In the introduction part, the interviewee was introduced to the topic, the visualization method and goals of the interview. The second part comprised a presentation of the case study area, scenarios, thematic integration, theoretical impacts of indicators and technical background. In the actual interview we asked first for the interviewee's ambitions of interacting with the

Figure 41 - Example of a densification scenario generated in ESRI's CityEngine of the case study area in Schlieren.

model (indicator setting and navigation). After demonstration of indicator influences by interactive modeling, we asked for stating preferences for a scenario referring to the indicators. Finally, the provided level of detail was assessed by the interviewees.

5. Preliminary 3D urban visualization model and pre-test results

First visualizations and pre-test results show a quite good acceptance of interactive modeling with ESRI's CityEngine system. In a first interview series with stakeholders and experts it was said that interactive modeling helps to understand the presented scenarios (see example in Figure 41). In these interviews, the participative part was applied as a semi-interactive survey. This means, the model parameters were directly shown in CityEngine. Positive feedback from stakeholders supports that this helps to understand the scenarios and their coherence with the indicators. The option to change camera positions within the visualization to get a close distance view to dwelling zones of special interest or positions with special view axes (Figure 42) was rated as a positive feature.

However, the interviewees did not want to navigate themselves through the model and change between the scenarios. Because of the interview structure and option for model interaction after only a short theoretical introduction, the participants asked rather for being navigated through the model. The most adverse point identified in this pre-test was the complexity of the CityEngine's user interface. Because of this and the big variety of indicators, the stakeholders were deterred to modify them and set up their own scenarios. It was not directly clear for them, where they have to set the parameters, because there are no options for designing any custom bars or buttons for indicator setting. For presentation mode a full screen option with custom possibility for rule and indicator setting is still missing in CityEngine.

Figure 42 - Example of different close up camera positions of two scenarios generated in ESRI's CityEngine.

Although the CityEngine system generally supports interactive change of scenes, for real interactivity in participatory situations the need of system recourses is a hindrance. For generating the scene, a 24GB RAM workstation with high-performance GPU and CPU was used. For large-scale visualization with included vegetation such a configuration is necessary to handle the changed model parameters re-rendering rapidly. In interview situation we had to use a mobile device, which has a comparatively bad system performance. Therefore, a preparation of the scene was inalienable – the renderings for all scenarios were done before the interviews and interactively modifying and re-renderings were only done for selected lots.

6. Discussion & conclusions

Our goal was to set up a framework suitable to integrate objective and subjective indicators for assessing urban landscape identity in participatory settings. To this end, we elaborated a workflow combining sophisticated data acquisition and 3D modeling and visualization approaches. Implementing the framework resulted in 3D visualizations with a rather high level of detail, which were linked to a set of indicators. The used techniques allowed visualizing large landscapes as static high realistic visualizations, which can display relevant aspects for assessing landscape identity. With regard to the visualization workflow, (semi-)automatic generation processes for CGA rules should be implemented in order to generate even more

Figure 43 - Future application of interactive modeling in stakeholder workshop (left) and in future online applications (right).

realistic landscapes with reduced effort. In the pre-test, the interactive modeling supported the interest of interviewees and helped them to understand scenario parameters. However, they did not try to interact with the setting of indicators or change the parameters themselves, which considerably can be ascribed to the complexity of the interface (van Schaik, 2010).

Further software options of the CityEngine are desirable, such as e.g. hiding complex parameter windows that are confusing for the interviewees. Next to already known benefits of visualizations as communication tool for common strategy development in stakeholder workshops (Figure 43, left), the software design allows new approaches for stakeholder involvement (Figure 43, right), which might be suitable for citizen-sourcing (Nam, 2012; Fritz et al., 2012).

Already existing solutions (e.g. RealityServer) can handle the high system requirements of interactive realistic real-time modeling. These techniques could be used for interactive online experiments to get general threshold values of indicators and use these for setting trade-offs in stakeholder workshops with experts. The variety of web application is high, so the integration of the models in game engines is also conceivable (Bishop, 2011), which run on nearly all mobile devices and operation systems. This flexibility offers also a high rate of return and the interviewees get an interactive user interface with navigation and indicator setting possibilities online. Current technical possibilities offer multiple options for an operationalization of qualitative factors like landscape aesthetics and identity. Although concepts of how to develop the supporting tools already exist, the lack of operable interfaces makes their implementation difficult. All methods of the modules in the presented workflow are rather sophisticated. The challenge is to design the interfaces between the modules in order to let the workflow run smoothly. Then, the resulting tool can really improve participative planning processes and potentially provide suitable means to also taken into account urban identity.

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Appendix I

Vorschau | [ger] [eng] | [standard] [barrierefrei]

PLUS
PLANNING OF LANDSCAPE AND URBAN SYSTEMS

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Demand Analysis
Communication & Visualization of
Ecosystem Service Information

Druckansicht vom 13.11.2014, 12:00

Bitte beachten Sie, dass Filter und Platzhalter in der Druckansicht prinzipbedingt nicht funktionieren. Fragen, die mittels PHP-Code eingebunden sind, werden nur eingeschränkt wiedergegeben.

Korrekturfahne **Variablenansicht** **PHP-Code ausblenden**

Seite 01

Welcome to the survey on "Visualization and Communication of Ecosystem Services"

This survey is part of a research project (EU - 7th framework OPERAs project - www.operas-project.eu) at the Chair of Planning of Landscape and Urban Systems - PLUS at ETH Zurich.

It aims at recording the demands and requirements of potential users of decision support platforms, tools and systems of ecosystem services information. The information you give will be incorporated into the (further) development of these supporting tools. You will have the opportunity to indicate concrete aspects, which will render the application of the tool more attractive to you.

The results will flow into the OPERAs and other projects and will published in scientific journals as well. Abstracts of the survey results will also published on www.ecosystemservices.ch/results.

A total of 34 questions are to be answered. To complete the entire survey will take you approximately 15-35 minutes. Your answers will be treated and evaluated anonymously.

The survey is also open to other projects. Contact us and recieve a code to use the survey in your project and thus to identify the needs of your project members, stakeholders or potential users.

Please click on "Next" to begin the questionnaire.

Seite 02

1. Group- & (Sub-) Project Identification

If you have received within a project or working group for this survey a code, please insert it here.

Otherwise, please click Next.

Seite 03

I1

2. Focus

Which special fields are you related to by your job?
Please select the fields you mostly work in (maximum 3 answers).

- ☐ economy
- ☐ forestry
- ☐ environmental damage / pollution
- ☐ construction
- ☐ farming / agriculture
- ☐ urban / landscape planning
- ☐ environment / nature
- ☐ communication
- ☐ climate / air
- ☐ politics
- ☐ soil / geology

- ☐ tourism / leisure / recreation
- ☐ natural hazards / risk prevention
- ☐ transportation
- ☐ biology
- ☐ energy / energy supplies
- ☐ fishing / hunting
- ☐ water / hydrology
- ☐ raw materials / natural resources / disposal
- ☐ research
- ☐ justice / law
- ☐ international aspects
- ☐ other: ____

Seite 04

Explanation of "decision support platforms"

Before we present you with the actual questions of the survey, we would like to explain briefly what "decision support platforms" are and what tasks they should perform.

These platforms provide (decision-making) support functions for practice and research in space-related issues. The focus lies on the conveying of information on ecosystem services and related topics. Ecosystem services are a variety of environmental services, such as providing food, drinking water and raw materials for production or the cultural contribution of the landscape that support the well-being of the people.

Geospatial content can be presented in different ways. In particular, indicators can be processed and viewed by different modes of representation. This allows to address different groups of users on specific topics. Even people who previously had no idea or no understanding of a topic or simply had no access to information could be reached.

In order to provide the necessary information on the platforms in sufficient quality for you, we depend on your answers to the following questions. They tell us your requirements for a decision support platform.

Seite 05

3. Scale identification

In what scales are you mostly operating within your professional activities or projects? (maximum 2 answers)

- ☐ global
- ☐ continental
- ☐ EU-wide
- ☐ national
- ☐ regional
- ☐ local
- ☐ other: ________

Seite 06

Explanation regarding applicability

Before continuing, we would like to explain briefly the potential application field hiding behind the term "decision-support platforms".

In their appearance the platforms resemble geographical (GIS) or spatial information systems. There also may be similarities in their functionality. However, compared to traditional information systems, the platforms allow broad access as a web application. They also enable people with no knowledge of the topic or the subject to use the contents by providing them on different levels of complexity (for example as "App"). Thus they differ from traditional Web GIS.

Seite 07
FA

4. Basic functions of decision support platforms

The function of decision support platforms can be further specialized. Which function(s) should generally be provided by such a platform?

- ☐ information (provision of content related information)
- ☐ communication (support of communication of content)
- ☐ exploration (exploration of content)
- ☐ analysis (evaluation of content)
- ☐ other function(s): ____________
- ☐ I don't know

Which of these functions associated with your occupation or projects is most important for you?

- ○ information
- ○ communication
- ○ exploration
- ○ analysis
- ○ other function(s): ____________
- ○ I don't know

Seite 08

5. Significance of basic functions

Please assess now the importance of these basic functions of a decision support platform in your professional activity or projects. Please assign the respective basic functions to a rank by dragging it holding the mouse button onto the desired rank ("drag & drop") or by a double click. (Rank 1 = high rating)

information | communication

exploration | analysis

other

rank 1

rank 2

rank 3

Seite 09
FA

6. Setting of application

Suppose a decision support platform would contain all necessary contents, information and functions for the purpose in question. How do you evaluate the application potential of this platform, depending on the situation?
Please move the slider to determine the benefits of a platform regarding the setting of the application, or click directly on the scale to set the slider. Please also bear in mind the relation of the ratings to each other.

	I don't know	no benefit … high benefit
personal application (independent application)		
application in a group (e.g. together with colleagues)		
public application (e.g. during a workshop or a presentation)		

Which of these application settings of a decision support platform would be most relevant for you?

- ○ personal application (independent application)
- ○ application in a group (e.g. together with colleagues)
- ○ public application (e.g. during a workshop or a presentation)
- ○ none
- ○ I don't know

- ○ I don't know

7. Other application settings

What other application settings for a decision support platform could you imagine to be useful in your occupation or projects?
Here you have the opportunity to name other application settings.

If you named further settings, please rate also their potential for the application of a decision support platform.
Please consider in your assessment also the relation to the before evaluated application settings.

	I don't know	no benefit	high benefit
further named setting(s)			

8. Functions in application

This section asks for possible support functions of a decision support platform in its practical application (completeness and transparency of content, information and functionalities given).
Which of these aspects in your occupation or projects could be supported by a decision support platform? Please consider in your assessment also the relations of different aspects to each other.

	I don't know	not given	strongly given
analyses of content			
obtain information about the content			

support of decision-making

support of voting

support in discussions

support of estimation

exploration of content

support of assessments

support of scenario developments

communication of content

Seite 12
F

9. Functions in application

You have now the opportunity to name other application functions, for which in your opinion a decision support platform would be useful.
Please name these other applications here, if applicable:

If you could name further applications, please indicate to which extent a platform could support this application. Please also note the relation to the functions previously evaluated.

	I don't know	not given	strongly given
further named application(s)			

Seite 13

10. Functions in application

Which of these functions would be most important for you personally in the application of a decision support platform? (maximum 2 answers)

- ☐ support in discussions
- ☐ support of decision-making
- ☐ support of scenario developments
- ☐ analyses of content

- support of assessments
- communication of content
- support of estimation
- obtain information about the content
- support of votings
- exploration of content
- "other application(s)" named

Seite 14
F1

11. Temporal application

How do you assess the overall benefit from a decision support platform for a project?

	I don't know	no benefit	high benefit
overall benefit for a project			

How do you assess the overall benefits of the relevant project stages in which a decision support platform would be used? Please consider once again the relations of the benefits of each stage to each other.

	I don't know	no benefit	high benefit
entry stage			
orientation / analysis stage			
planning stage (rough planning)			
information / decision stage			
implementation stage			
evaluation stage / quality management			
other			

Please name the "other" stage(s) in the rating above, for which a decision support platform could be useful.

Seite 15

12. Significance of temporal application

Please rate the three stages of the project which would benefit most from a decision support platform. For this, please assign a rank to each phase according to its significance. (rank 1 = high rating)

- entry stage
- implementation stage
- evaluation stage / quality manag.
- other
- orientation / analysis stage
- planning stage (rough planing)
- information / decision stage

rank 1

rank 2

rank 3

Seite 16

At what intervals should a decision support platform generally be used in projects?

- ○ constantly (for any occasion / in all stages)
- ○ regularly (on most occasions / in most stages)
- ○ occasionally (on occasions / in stages in which a decision support platform provides a specific function)

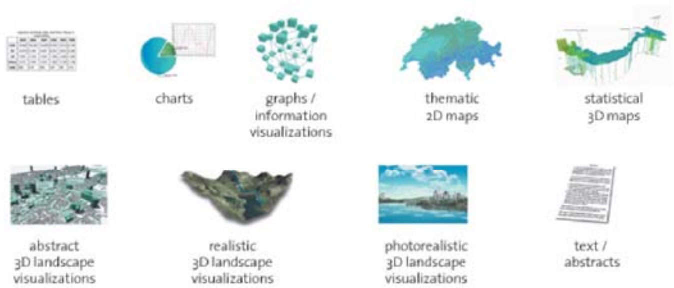
- ◯ rarely (only when there is a direct need / request)
- ◯ not at all (integration on occasions / in stages is deliberately avoided)
- ◯ as follows: ____________
- ◯ I don't know

Seite 17

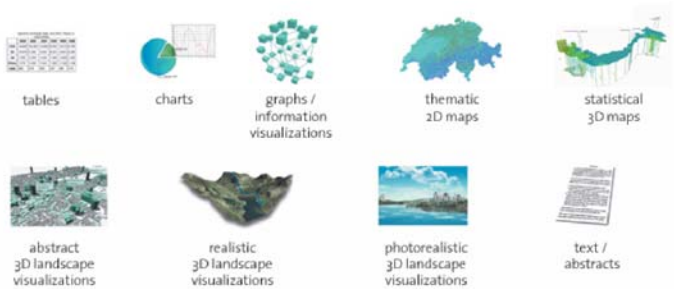
Explanation of representations and visualizations

Topic contents can usually be presented by different representation types. Represented appropriately contents can be clarified as well as read and understood better by the user. On the other hand, contents may be misinterpreted or not interpreted at all when unsuitable types of representations are used.

The contents on decision support platforms regarding space-related topics and projects often represent complex interrelationships of various factors. Possible types of representation to communicate such contents are, for example, information visualizations or 3D visualizations.



Seite 18
D3



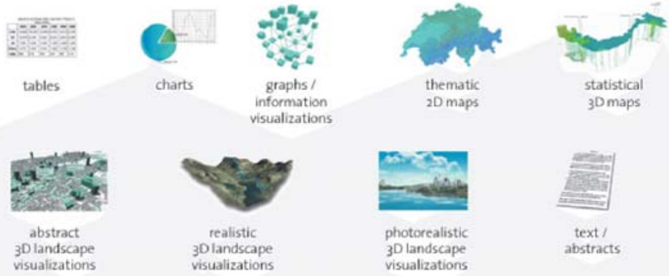
13. Significance of representation type

Each representation type has its advantages and disadvantages in terms of interpretation and accuracy. How do you assess these types of representation as a potential information carrier for the contents of your professional activity or projects?
Please also consider the relation of the assessed potentials to each other.

	I don't know	not meaningful … most meaningful
tables (contents and their values listed by tables)		
charts (e.g. pie-, bar-, line charts)		
graphs / information visualizations (e.g. representation of dependencies)		
thematic 2D maps (combinable maps edited by topic)		
statistical 3D maps (e.g. building heights related to building value)		
abstract 3D landscape visualizations (e.g. buildings coloured by height)		
realistic 3D landscape visualizations (all contents are displayed as realistically as possible)		
photorealistic 3D landscape visualizations (the visual quality of the representation looks similar to a real photographic picture)		
texts / abstracts		
other representation types		

Please name, if applicable, the relevant “other representation types”

Seite 19

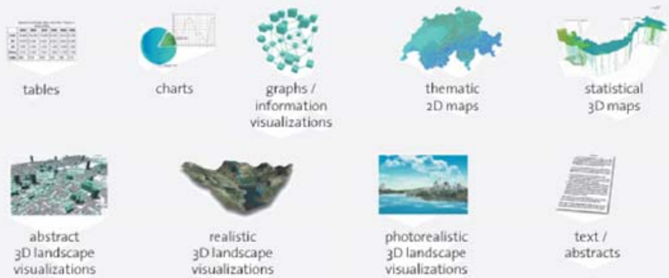


14. Significance of representation type

What types of representation would you personally prefer for your professional activities / projects (maximum 2 answers)

- ☐ tables (contents and their values listed by tables)
- ☐ charts (e.g. pie-, bar-, line charts)
- ☐ graphs / information visualizations (e.g. representation of dependencies)
- ☐ thematic 2D maps (combinable maps edited by topic)
- ☐ statistical 3D maps (e.g. building heights related to building value)
- ☐ abstract 3D landscape visualizations (e.g. buildings coloured by height)
- ☐ realistic 3D landscape visualizations (all contents are displayed as realistically as possible)
- ☐ photorealistic 3D landscape visualizations (the visual quality of the representation looks similar to a real photographic picture)
- ☐ texts / abstracts
- ☐ other representation types

Seite 20

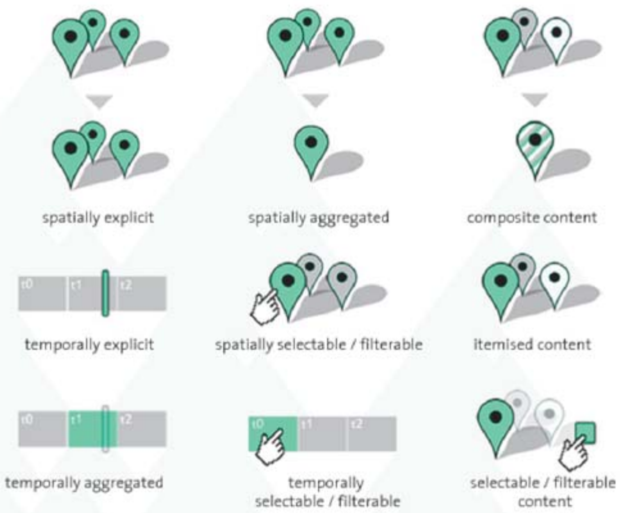


15. Significance of representation type

What types of representation would, in your opinion, be preferred by the people involved in your professional occupation or in your projects? (maximum 2 answers)

- ☐ tables (contents and their values listed by tables)
- ☐ charts (e.g. pie-, bar-, line charts)
- ☐ graphs / information visualizations (e.g. representation of dependencies)
- ☐ thematic 2D maps (combinable maps edited by topic)
- ☐ statistical 3D maps (e.g. building heights related to building value)
- ☐ abstract 3D landscape visualizations (e.g. buildings coloured by their height)
- ☐ realistic 3D landscape visualizations (all contents are displayed as realistically as possible)
- ☐ photorealistic 3D landscape visualizations (the visual quality of the representation looks similar to a real photographic picture)
- ☐ texts / abstracts
- ☐ other representation types

Seite 21
D0



16. Significance of display type

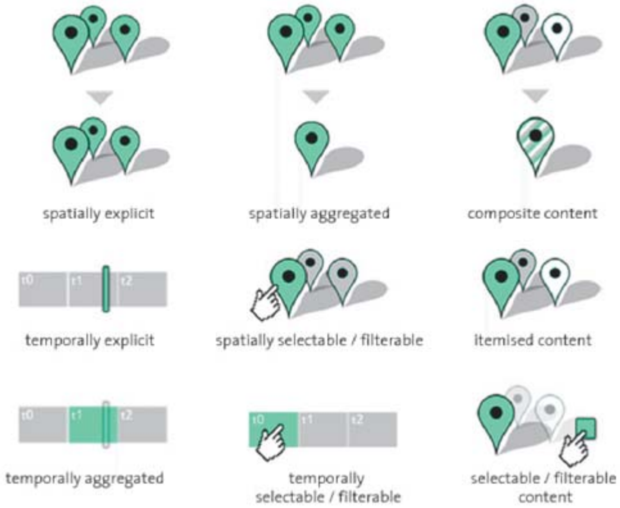
Information can be presented by the type of representation but also by a deliberately (more) precise / imprecise display.
This can be done – depending on the information -

- spatially (e.g. exactly / inexactly located information),
- temporally (e.g. for scenarios and time courses) and also
- by content (e.g. aggregation of factors of an ecosystem service).

Which display type is, in your opinion, most meaningful for the contents of your projects or occupation?

- ☐ spatially explicit (quality ratings are spatially exactly located)

- [ ] spatially aggregated (different spatially located quality ratings are aggregated)
- [ ] temporally explicit (quality ratings are temporally corresponding e.g. to a scenario)
- [ ] temporally aggregated (quality ratings are aggregated by period e.g. of time courses)
- [ ] spatially selectable / filterable (quality ratings can selected/filtered by location)
- [ ] temporally selectable / filterable (quality ratings can be selected/filtered for specific periods/stages)
- [ ] selectable / filterable contents (quality ratings can be selected/filtered e.g. by constraints)
- [ ] composite contents (quality ratings of an indicator are displayed e.g. without underlying and influencing factors)
- [ ] itemized contents (quality ratings of an indicator are displayed e.g. by values of underlying and influencing factors)
- [ ] other properties



17. Significance of display type

Which of these types of representation are most important for you? (maximum 2 answers)

- [ ] spatially explicit
- [ ] spatially aggregated
- [ ] temporally explicit
- [ ] temporally aggregated
- [ ] spatially selectable / filterable
- [ ] temporally selectable / filterable
- [ ] selectable / filterable content

- ☐ composite contents
- ☐ other properties
- ☐ itemized contents

Seite 23
D1


global


continental


EU-wide


national


regional


local

18. Display scale
On what scale is the information presented in your professional activity and your projects?

- ☐ global
- ☐ continental
- ☐ EU-wide
- ☐ national
- ☐ regional
- ☐ local
- ☐ other: ____
- ☐ I don't know

Which scale(s) would you personally prefer regarding the readability of the contents of your professional activities and projects? (maximum 2 answers)

- ☐ global
- ☐ continental
- ☐ EU-wide
- ☐ national
- ☐ regional
- ☐ local
- ☐ other: ____
- ☐ I don't know

Seite 24

19. Time horizon
Over what time horizon should information be shown about future states, if necessary?
Please select the desired time horizon.

1	2	3	4	5	6	7	8	9	10	25	50	75	100	>100	no need

year(s

Seite 25

Now, you are soon done.

Seite 26

Explanation regarding the interaction with contents

Decision support platforms provide interaction possibilities to examine the contents and the information according to own interests. These interests may be focused spatially or by content. A appropriate controls allow the selection of and navigation through desired contents or spatial interests.

We would like to present here a schematic platform user interface. The platform, available as a web application, could include, for example, a controllable display window to show the spatial contents, controls for displaying and controlling content as well as more information about the contents.

Depending on topic, contents and user focus, these elements could be adapted and provided with further functions. What other functions these are and in what situations they may be applied, we hope to learn from your following responses and judgements.

Seite 27
IF

20. Availability of functionalities

Which platform functionality is most important for you personally regarding the application of a decision support platform? (maximum 2 answers each category)

General functionalities

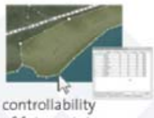
- ☐ storage of contents
- ☐ search for contents (e.g. by values)
- ☐ personalized arrangement of contents (e.g. array of representations)
- ☐ import of contents
- ☐ personalized representation types (e.g. definable classes, color values etc.)
- ☐ export of data
- ☐ export of contents
- ☐ printing of contents
- ☐ further help regarding the contents (e.g. comments on contents, reference to literature etc.)
- ☐ general help (e.g. for the use of functions)
- ☐ other: ____

Navigation

- ☐ interactive 2D navigation (selection and zoom of map frame: pan, zoom, rotate)
- ☐ interactive chronological navigation of time courses
- ☐ direct entry of scales for representation types (e.g. 1:25.000)

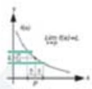
- ☐ direct entry of coordinates (e.g. for map section)
- ☐ interactive 3D navigation (free choice of views incl. oblique views)
- ☐ navigation by defined views/map sections (e.g. by bookmarks)
- ☐ other: ______

Seite 28
IF



controllability of future states by changing spatial characteristics

controllability of future states by chaning parameters



definition of future states by objectives

filtering content (by values / topic)

21. Availability of functionalities

Which platform functionality with respect to the controllability of contents is most important for you personally regarding the application of a decision support platform?

Controllability of contents

- ○ controllability of future states by spatial characteristics (e.g. change of land use)
- ○ controllability of future states by parameters (e.g. by change of weightings)
- ○ definition of future states by objectives (e.g. by setting future constraints)
- ○ filtering of contents (e.g. by value ranges, topic)
- ○ other: ______

Seite 29
IF

22. Significance of functionalities

Which of the previously characterized categories of functionalities in a decision support platform would be more important to you?
Please assign a rank to the mentioned categories according to their importance for you by moving the function to the respective rank holding the mouse button (drag & drop), or by double clicking. (rank 1 = high rating).

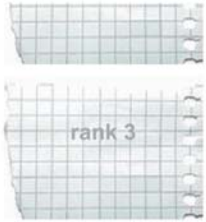
general functionalities

controllability of contents

navigation

rank 1

rank 2



Seite 30
AB

23. Use

Could you imagine to use a decision support platform in your professional activity or in your projects?

- ○ yes
- ○ no
- ○ possibly
- ○ under certain preconditions
- ○ other: ______
- ○ I don't know

If you like, you may give a reason for your decision or comment on it here:

Seite 31
AB

24. Demand analysis for platform users by own use

Suppose you want to use a decision support platform in your professional activity or in your projects. Would you consider it useful to conduct a similar survey in relation to the requirements of this platform with the potential users or the project participants?

- ○ yes
- ○ no
- ○ possibly
- ○ under certain preconditions
- ○ no use of such a platform
- ○ other: ______
- ○ I don't know

If you like, you may give a reason for your decision or comment on it here:

Seite 32
IND

25. Use of indicators

Are you dealing with indicators on spatial aspects, such as environmental and landscape quality or ecosystem services, in your profession or your projects?

- ◯ Yes, regularly.
- ◯ Yes, sometimes.
- ◯ Yes, but rarely.
- ◯ No, not at all.
- ◯ I don't know

If yes, in what context do you use such indicators?
We would be grateful if you could give us more details.

Seite 33
IND

graphs / information visualizations

thematic 2D maps

statistical 3D maps

abstract 3D landscape visualizations

realistic 3D landscape visualizations

photorealistic 3D landscape visualizations

26. Additional representation types for indicators

If you are dealing with environmental, landscape, or ecosystem indicators in your profession or your projects, could you imagine that these could be (additionally) usefully and helpfully presented by one / more of the above displayed representation types?

- ◯ yes
- ◯ under certain circumstances
- ◯ no

◯ I don't use indicators
◯ I don't know

If you like, you may give a reason for your decision or comment on it here:

Seite 34
IND

27. Additional representations for indicators
Would it be helpful for your professional activity or projects, if indicators could be presented by different representation types?

◯ yes
◯ under certain circumstances
◯ no
◯ I don't know

If you like, you may give a reason for your decision or comment on it here:

Seite 35
IND

28. Indicators
Would you like to have shown indicators, which have not been displayable so far or difficult to prepare?

◯ yes
◯ under certain circumstances
◯ no
◯ I don't know

If you like, you may give a reason for your decision or comment on it here:

Seite 36
KOM

29. Comments & additions

If you think we have disregarded or omitted important aspects or questions, we would be very grateful if you could tell us.
Please let us know your comments and additions:

Seite 37
I0

30. Age

How old are you?

- ◯ under 25 years
- ◯ 25 to 34 years
- ◯ 35 to 44 years
- ◯ 45 to 54 years
- ◯ 55 to 65 years
- ◯ over 65 years

31. Occupational function

In order to contextualize the information you give us, it will be helpful if you tell us your occupational function.

- ◯ assistance
- ◯ specialist / processing
- ◯ specialist of subject area
- ◯ head of subject area
- ◯ head of department
- ◯ (first) leadership position
- ◯ research associate
- ◯ other

32. Field of employment

Which field do you work in?

- ○ administration
- ○ private industry
- ○ research
- ○ other

Seite 38

33. May we contact you again?

In order to guarantee specific implementation and development based on your demands on "decision support platforms", it would be helpful to be able to check with you if necessary. Please, let us therefore know whether you agree if we contact you again. If so, please indicate your e-mail address below..

e-mail address: ☐ I would prefer not to be contacted again in this matter.

Letzte Seite

Thank you for your participation!

We would like to sincerely thank you for your help.

Thomas Klein, ETH Zurich - PLUS, Wolfgang-Pauli-Str. 15, 8093 Zürich (Switzerland), E-Mail: thomas.klein@nsl.ethz.ch

OPERAs

SEVENTH FRAMEWORK PROGRAMME

Appendix II

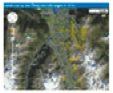
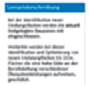
Table A1
Overview of the types of representation (AOIs) with their characteristics (AOI coverage in DSS, interactive functionality), and information content.

(AOI)	Representation type	Information	Interactive	Time series*	AOI coverage**
R0	Realistic landscape visualization	Landscape scenery of municipality of Visp that shows a settlement area in 2034	no	no	7.4%
R1	Pie and bar chart	Land-use information for study region with additional time behavior for 2014, 2019, 2024, 2029, 2034	yes	yes	9.3%
R2	Thematic 2D map	Land-use information for study region in 2034	yes	no	11.9%
R3	Photo-realistic landscape visualization	Landscape scenery of municipality of Saas-Fee that shows a settlement area in 2034	no	no	10.6%
R4	Text/abstract	Short abstract about scenario preconditions and the general behavior	no	no	3.5%
R5	Icons	Scenario preconditions	yes	no	1.0%
R6	Stacked bar chart	Potential of ecosystem services loss for each municipality in 2034	no	no	10.6%
R7	Stacked bar chart	Settlement area in 2014 and 2034 for each municipality	no	yes	10.0%
R8	Grouped bar chart	Total agricultural production with the food products milk, meat and crop for 2014, 2019, 2024, 2029, 2034	no	yes	10.0%

* Information is provided for multiple years
** 25.80% of DSS coverage consist of background, task information, button to switch between scenarios, institute icons that was measured as “white space” and was not further considered in the analysis

Table A2

Mean values and standard deviations (SDs) of dwell times (DTs) in milliseconds for each representation type by task. Per task highest mean value for participant groups (Hypothesis 2) is marked in bold as well the three most used types of representation in total. Highlighted colors for types of representation correspond to the AOIs.

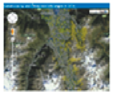
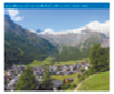
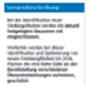
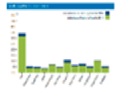
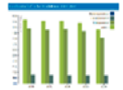
		 R0		 R1		 R2		 R3		 R4		 R5		 R6		 R7		 R8	
Task	**Region***	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
2	no	3.255	2.966	12.939	11.225	7.615	6.280	4.493	4.023	4.318	6.510	1.728	3.168	**22.107**	12.263	15.907	7.633	10.189	6.830
	yes	3.722	4.746	8.961	8.201	9.518	9.844	6.039	7.095	1.751	3.224	488	1.256	16.989	10.437	**17.553**	10.638	12.710	9.338
	total	3.493	3.962	10.911	9.954	8.585	8.306	5.281	5.820	3.009	5.241	1.096	2.461	**19.498**[1]	11.600	**16.746**[2]	9.279	**11.475**[3]	8.263
3	no	3.538	3.260	12.344	12.125	9.698	9.861	2.977	2.929	8.833	15.361	5.564	8.797	**18.748**	14.268	14.570	7.842	7.173	6.038
	yes	4.615	8.080	9.340	10.282	8.905	9.380	5.204	8.054	3.583	8.717	1.829	4.037	**17.650**	12.522	16.968	11.528	6.879	6.533
	total	4.087	6.198	**10.812**[3]	11.269	9.293	9.579	4.113	6.178	6.156	12.641	3.660	7.021	**18.189**[1]	13.351	**15.793**[2]	9.919	7.023	6.266
4	no	4.941	8.173	5.188	7.674	**36.034**	28.843	3.766	5.000	1.107	3.012	966	2.747	19.137	16.658	16.900	15.457	2.728	3.982
	yes	4.170	7.778	6.581	8.301	20.965	25.176	3.799	6.074	1.252	3.912	482	1.413	**21.562**	20.986	20.901	17.982	3.047	3.646
	total	4.548	7.944	5.898	7.991	**28.352**[1]	27.946	3.783	5.546	1.181	3.484	720	2.174	**20.373**[2]	18.934	**18.940**[3]	16.830	2.891	3.799
5	no	4.872	5.690	7.215	8.337	12.639	14.361	3.297	4.057	4.296	7.632	2.358	4.121	**20.857**	12.593	20.435	12.495	4.762	5.191
	yes	4.679	5.043	9.553	10.921	13.381	15.985	4.169	7.680	2.765	4.312	1.834	3.647	**17.961**	12.559	15.401	9.773	5.817	5.587
	total	4.773	5.344	8.407	9.764	**13.017**[3]	15.140	3.741	6.161	3.516	6.184	2.091	3.876	**19.380**[1]	12.597	**17.869**[2]	11.418	5.300	5.396
6	no	6.827	9.982	5.303	8.478	14.608	17.498	6.447	7.417	3.283	7.134	1.633	4.488	**32.432**	19.294	13.178	10.210	2.774	3.512
	yes	3.374	4.570	7.369	8.292	6.503	7.934	3.970	4.959	2.521	6.782	1.142	2.112	**33.722**	20.730	13.203	8.599	4.431	4.621
	total	5.067	7.867	6.356	8.406	**10.476**[3]	14.032	5.184	6.377	2.895	6.933	1.383	3.476	**33.090**[1]	19.950	**13.191**[2]	9.376	3.618	4.178
7	no	**17.492**	11.275	8.062	10.361	15.654	15.485	17.136	11.339	2.910	5.202	2.321	4.663	13.819	15.708	5.670	5.937	3.286	3.720
	yes	**17.663**	16.337	6.539	6.860	17.570	16.419	13.957	10.871	1.497	3.841	1.296	2.907	10.465	12.262	6.492	6.342	3.386	4.169
	total	**17.579**[1]	14.016	7.286	8.742	**16.631**[2]	15.918	**15.515**[3]	11.162	2.190	4.591	1.799	3.883	12.109	14.088	6.089	6.130	3.337	3.936
8	no	2.406	1.751	14.764	12.446	9.262	10.344	2.228	2.291	4.314	8.216	2.979	5.923	**39.227**	23.291	7.451	5.144	5.312	5.373
	yes	3.799	5.233	12.257	10.276	8.013	8.699	4.388	4.797	3.264	7.328	1.736	3.077	**30.351**	18.858	8.640	7.445	6.731	6.070
	total	3.116	3.976	**13.486**[2]	11.404	**8.625**[3]	9.514	3.329	3.917	3.778	7.755	2.345	4.711	**34.702**[1]	21.509	8.057	6.417	6.035	5.755

* between-subjects factor variable: *participants' relation to the region* (Hypothesis 2)

[1] = type of representation with the longest dwell time, [2] = type of representation with the second longest dwell time, [3] = type of representation with the third longest dwell time

Table A3

Mean values and standard deviations (SD) of fixation counts (FC) for each representation type by task. Per task highest mean value for participant groups (Hypothesis 2) is marked in bold as well the three most used types of representation in total. Highlighted colors for types of representation correspond to the AOIs.

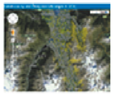
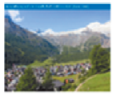
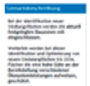
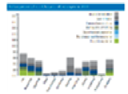
		 R0		 R1		 R2		 R3		 R4		 R5		 R6		 R7		 R8	
Task	Region*	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2	no	13,50	11,77	47,14	37,57	29,86	22,56	18,02	14,59	16,82	23,11	6,18	9,72	**83,54**	41,25	63,24	27,03	41,12	26,13
	yes	15,92	18,36	35,77	29,38	39,19	36,75	25,00	26,15	7,35	12,67	2,21	5,45	68,50	40,22	**72,02**	39,97	53,08	34,63
	total	14,74	15,46	41,34	33,96	34,62	30,84	21,58	21,46	11,99	19,04	4,16	8,05	**75,87**[1]	41,23	**67,72**[2]	34,36	**47,22**[3]	31,19
3	no	13,14	11,06	42,74	38,91	30,06	27,32	9,86	8,68	32,80	56,64	19,48	29,68	**69,02**	47,12	53,62	27,16	26,16	17,53
	yes	17,44	24,60	34,58	32,74	32,88	29,51	18,54	24,78	14,44	33,96	7,50	14,71	**70,17**	45,18	66,87	41,61	27,69	23,75
	total	15,33	19,23	**38,58**[3]	35,95	31,50	28,35	14,28	19,12	23,44	47,16	13,37	23,93	**69,61**[1]	45,92	**60,37**[2]	35,73	26,94	20,84
4	no	17,28	24,54	18,80	25,93	**107,54**	84,17	11,96	14,70	4,60	12,67	2,98	8,93	65,36	51,18	59,54	51,60	11,20	15,49
	yes	16,42	27,18	24,12	28,17	71,79	77,95	14,87	22,26	5,33	15,41	2,02	5,78	**79,19**	70,97	78,63	61,70	12,92	15,03
	total	16,84	25,79	21,51	27,10	**89,31**[1]	82,63	13,44	18,90	4,97	14,07	2,49	7,47	**72,41**[2]	62,15	**69,27**[3]	57,50	12,08	15,21
5	no	15,82	16,90	26,06	24,90	40,28	43,51	10,36	10,79	16,72	29,84	8,96	15,16	**76,22**	42,96	74,18	40,81	18,86	18,08
	yes	18,21	19,02	35,63	36,66	48,15	51,00	14,98	22,77	11,33	17,28	7,15	13,57	**69,65**	45,04	61,12	33,74	25,71	22,50
	total	17,04	17,96	30,94	31,66	**44,29**[3]	47,41	12,72	17,99	13,97	24,29	8,04	14,33	**72,87**[1]	43,94	**67,52**[2]	37,76	22,35	20,64
6	no	19,66	24,33	19,32	27,39	43,92	47,34	18,50	17,13	13,04	28,14	5,76	13,28	**112,02**	62,49	47,82	33,79	11,86	14,40
	yes	13,50	16,47	28,87	29,04	25,10	26,90	15,17	17,74	10,52	27,74	5,02	9,11	**126,06**	65,56	53,08	29,55	18,83	18,39
	total	16,52	20,83	24,19	28,51	**34,32**[3]	39,27	16,80	17,44	11,75	27,83	5,38	11,30	**119,18**[1]	64,14	**50,50**[2]	31,65	15,41	16,84
7	no	**55,82**	34,97	28,84	34,85	47,26	39,62	49,66	36,32	11,86	20,45	8,18	15,85	48,66	46,01	22,72	20,33	13,52	14,06
	yes	**60,79**	47,05	26,27	25,61	60,63	50,83	46,40	32,71	6,25	14,93	5,25	11,54	43,15	48,67	26,35	23,94	14,65	16,83
	total	**58,35**[1]	41,44	27,53	30,37	**54,08**[2]	45,95	**48,00**[3]	34,39	9,00	17,98	6,69	13,83	45,85	47,23	24,57	22,21	14,10	15,47
8	no	9,28	6,22	49,68	39,89	31,16	33,44	7,58	6,97	16,54	30,38	9,94	17,37	**133,00**	68,60	29,64	18,76	19,24	18,06
	yes	14,73	18,63	44,79	34,95	30,27	31,17	16,25	15,63	13,73	29,38	7,44	12,39	**117,50**	71,93	34,46	27,22	26,69	23,36
	total	12,06	14,20	**47,19**[2]	37,35	30,71	32,14	12,00	12,88	15,11	29,76	8,67	15,02	**125,10**[1]	70,40	**32,10**[3]	23,47	23,04	21,16

* between-subjects factor variable: *participants' relation to the region* (Hypothesis 2)

[1] = most fixated representation type, [2] = second most fixated representation type, [3] = third most fixated representation type

Table A4

Mean values and standard deviations (SD) of revisits (RV) for each representation type by task. The per-task highest mean value for subject groups (Hypothesis 2) is marked in bold as well the three most used types of representation in total. Highlighted colors for types of representation correspond to the AOIs.

		R0		R1		R2		R3		R4		R5		R6		R7		R8	
Task	Region*	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2	no	3,64	3,38	5,86	4,47	7,34	5,79	4,28	2,96	1,74	2,08	0,92	1,38	10,78	6,66	**11,22**	6,01	5,78	3,32
	yes	3,23	3,60	5,29	3,89	9,02	6,72	5,13	5,23	1,25	2,09	0,35	0,81	8,44	5,85	**11,04**	6,64	6,52	3,63
	total	3,43	3,48	5,57	4,17	**8,20**[3]	6,31	4,72	4,27	1,49	2,09	0,63	1,16	**9,59**[2]	6,34	**11,13**[1]	6,31	6,16	3,49
3	no	3,48	2,75	6,00	3,52	6,20	3,30	2,46	2,10	3,10	4,67	3,04	4,74	11,64	7,06	**12,12**	7,27	4,46	2,77
	yes	4,23	3,57	5,29	3,76	7,67	5,48	3,87	4,03	1,60	2,93	1,42	3,18	12,31	7,34	**13,73**	7,45	4,85	3,89
	total	3,86	3,20	5,64	3,64	**6,95**[3]	4,58	3,18	3,29	2,33	3,93	2,22	4,08	**11,98**[2]	7,18	**12,94**[1]	7,37	4,66	3,38
4	no	3,30	3,79	3,84	5,04	8,96	5,02	2,40	2,73	0,54	1,20	0,38	1,34	10,24	7,65	**10,32**	8,49	2,30	2,90
	yes	3,15	3,59	3,81	4,32	7,77	6,19	3,15	4,12	0,69	1,38	0,33	0,88	9,56	6,62	**11,21**	6,51	2,85	3,70
	total	3,23	3,67	3,82	4,66	**8,35**[3]	5,65	2,78	3,51	0,62	1,29	0,35	1,12	**9,89**[2]	7,12	**10,77**[1]	7,52	2,58	3,33
5	no	4,20	4,18	5,28	3,93	7,64	5,07	2,62	3,06	2,52	4,98	1,88	3,74	13,40	8,36	**15,26**	8,59	4,12	4,16
	yes	3,60	3,55	5,17	4,02	8,35	5,53	3,31	3,65	0,79	1,16	1,13	2,47	11,17	6,43	**12,29**	7,00	4,96	3,59
	total	3,89	3,87	5,23	3,96	**8,00**[3]	5,30	2,97	3,38	1,64	3,67	1,50	3,16	**12,26**[2]	7,48	**13,75**[1]	7,92	4,55	3,88
6	no	3,24	3,08	3,26	3,06	6,00	4,80	3,64	3,39	1,32	2,64	0,90	1,80	**12,24**	7,28	10,78	6,91	2,50	2,60
	yes	2,92	3,20	4,38	3,86	5,46	5,01	3,06	3,44	1,08	2,50	1,04	2,34	**13,31**	8,39	11,33	6,93	3,29	2,91
	total	3,08	3,13	3,83	3,52	**5,73**[3]	4,89	3,34	3,41	1,20	2,56	0,97	2,08	**12,78**[1]	7,85	**11,06**[2]	6,89	2,90	2,78
7	no	**9,86**	5,23	4,82	4,94	8,96	5,33	7,88	5,18	1,34	2,20	1,18	1,66	7,94	5,27	6,04	4,48	2,88	2,86
	yes	**9,60**	5,18	5,31	4,30	9,35	4,61	8,44	4,68	0,73	1,60	0,63	1,51	7,48	6,16	6,25	5,11	2,92	2,90
	total	**9,73**[1]	5,18	5,07	4,61	**9,16**[2]	4,95	**8,17**[3]	4,91	1,03	1,93	0,90	1,60	7,71	5,72	6,15	4,79	2,90	2,86
8	no	2,66	2,17	5,72	4,67	5,10	3,54	1,92	1,96	1,68	2,58	1,44	2,42	**12,12**	5,63	6,98	3,58	3,02	2,43
	yes	3,79	3,24	6,23	4,34	5,73	4,48	4,00	3,42	1,52	2,28	1,25	2,09	**12,46**	6,32	8,12	5,58	4,08	2,64
	total	3,24	2,82	**5,98**[3]	4,49	5,42	4,04	2,98	2,98	1,60	2,42	1,34	2,25	**12,29**[1]	5,96	**7,56**[2]	4,72	3,56	2,58

* between-subjects factor variable: *participants' relation to the region* (Hypothesis 2)

[1] = most revisited representation type, [2] = second most revisited representation type, [3] = third most revisited representation type

Table A5
Estimated ET variable measures.

		Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
Dwell Time (DT)	R0	6096,658	415,118	5273,076	6920,240
	R1	9029,566	391,375	8253,088	9806,043
	R2	13597,474	764,503	12080,721	15114,226
	R3	5847,798	364,093	5125,448	6570,148
	R4	3263,900	407,929	2454,580	4073,220
	R5	1882,673	223,079	1440,091	2325,255
	R6	22502,088	782,258	20950,111	24054,066
	R7	13805,064	538,464	12736,767	14873,361
	R8	5658,932	242,629	5177,563	6140,300
Fixation Count (FC)	R0	21,537	1,319	18,920	24,154
	R1	33,043	1,276	30,511	35,575
	R2	45,579	2,357	40,902	50,255
	R3	19,797	1,176	17,464	22,129
	R4	12,952	1,601	9,776	16,127
	R5	7,005	,786	5,445	8,566
	R6	83,004	2,694	77,658	88,349
	R7	53,091	1,944	49,234	56,949
	R8	22,967	,944	21,095	24,839
Revisits (RV)	R0	4,350	,202	3,950	4,750
	R1	5,019	,236	4,551	5,486
	R2	7,396	,317	6,768	8,025
	R3	4,012	,211	3,594	4,429
	R4	1,421	,157	1,109	1,733
	R5	1,135	,138	,861	1,410
	R6	10,935	,445	10,053	11,817
	R7	10,477	,397	9,689	11,266
	R8	3,894	,172	3,553	4,236

Table A6: Test of within-subjects contrasts of dwell times

Source				Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power a
Task_ * Representation Type_	Dwell Time_	Level 1 vs. Level 7	Level 1 vs. Level 2	884994183,364	1	884994183,364	3,632	,060	,035	3,632	,471
			Level 2 vs. Level 3	631762259,411	1	631762259,411	1,797	,183	,018	1,797	,264
			Level 3 vs. Level 4	419753106,775	1	419753106,775	2,628	,108	,026	2,628	,362
			Level 4 vs. Level 5	749850027,798	1	749850027,798	7,429	,008	,069	7,429	,770
			Level 5 vs. Level 6	25011970,192	1	25011970,192	,302	,584	,003	,302	,085
			Level 6 vs. Level 7	19959097418,362	1	19959097418,362	34,594	,000	,257	34,594	1,000
			Level 7 vs. Level 8	58364478509,730	1	58364478509,730	82,645	,000	,452	82,645	1,000
			Level 8 vs. Level 9	1081062205,315	1	1081062205,315	6,637	,011	,062	6,637	,723
		Level 2 vs. Level 7	Level 1 vs. Level 2	1352541196,914	1	1352541196,914	4,837	,030	,046	4,837	,586
			Level 2 vs. Level 3	1132245183,282	1	1132245183,282	2,495	,117	,024	2,495	,346
			Level 3 vs. Level 4	1438525,482	1	1438525,482	,007	,932	,000	,007	,051
			Level 4 vs. Level 5	273100738,452	1	273100738,452	1,388	,242	,014	1,388	,215
			Level 5 vs. Level 6	118944729,127	1	118944729,127	,613	,436	,006	,613	,121
			Level 6 vs. Level 7	32774443182,962	1	32774443182,962	43,697	,000	,304	43,697	1,000
			Level 7 vs. Level 8	60273965699,261	1	60273965699,261	72,168	,000	,419	72,168	1,000
			Level 8 vs. Level 9	4603453984,099	1	4603453984,099	29,409	,000	,227	29,409	1,000
		Level 3 vs. Level 7	Level 1 vs. Level 2	8403791863,289	1	8403791863,289	38,427	,000	,278	38,427	1,000
			Level 2 vs. Level 3	77042787551,107	1	77042787551,107	68,568	,000	,407	68,568	1,000
			Level 3 vs. Level 4	38325954189,193	1	38325954189,193	49,039	,000	,329	49,039	1,000
			Level 4 vs. Level 5	969601769,044	1	969601769,044	12,562	,001	,112	12,562	,939
			Level 5 vs. Level 6	97155191,242	1	97155191,242	1,744	,190	,017	1,744	,258
			Level 6 vs. Level 7	16721825823,459	1	16721825823,459	19,965	,000	,166	19,965	,993
			Level 7 vs. Level 8	65237489947,010	1	65237489947,010	57,224	,000	,364	57,224	1,000
			Level 8 vs. Level 9	19953644967,582	1	19953644967,582	66,799	,000	,400	66,799	1,000
		Level 4 vs. Level 7	Level 1 vs. Level 2	4713585768,626	1	4713585768,626	22,644	,000	,185	22,644	,997
			Level 2 vs. Level 3	9200151030,167	1	9200151030,167	18,842	,000	,159	18,842	,990
			Level 3 vs. Level 4	1589054243,967	1	1589054243,967	4,546	,035	,043	4,546	,560
			Level 4 vs. Level 5	47497717,721	1	47497717,721	,370	,544	,004	,370	,092
			Level 5 vs. Level 6	1180,481	1	1180,481	,000	,997	,000	,000	,050
			Level 6 vs. Level 7	23306241830,180	1	23306241830,180	35,704	,000	,263	35,704	1,000
			Level 7 vs. Level 8	65020986089,822	1	65020986089,822	92,091	,000	,479	92,091	1,000

	Level 8 vs. Level 9	11465287654,710	1	11465287654,710	54,100	,000	,351	54,100	1,000
Level 5	Level 1 vs. Level 2	8578449907,883	1	8578449907,883	30,715	,000	,235	30,715	1,000
vs.	Level 2 vs. Level 3	8429780696,293	1	8429780696,293	16,863	,000	,144	16,863	,982
Level 7	Level 3 vs. Level 4	32695,935	1	32695,935	,000	,992	,000	,000	,050
	Level 4 vs. Level 5	791662658,569	1	791662658,569	6,197	,014	,058	6,197	,693
	Level 5 vs. Level 6	707856,006	1	707856,006	,008	,931	,000	,008	,051
	Level 6 vs. Level 7	56116385,075	1	56116385,075	,064	,801	,001	,064	,057
	Level 7 vs. Level 8	4794142218,002	1	4794142218,002	4,978	,028	,047	4,978	,599
	Level 8 vs. Level 9	5834525312,014	1	5834525312,014	36,141	,000	,265	36,141	1,000
Level 6	Level 1 vs. Level 2	43624889214,822	1	43624889214,822	101,804	,000	,504	101,804	1,000
vs.	Level 2 vs. Level 3	20515434297,527	1	20515434297,527	36,065	,000	,265	36,065	1,000
Level 7	Level 3 vs. Level 4	1853330877,254	1	1853330877,254	3,974	,049	,038	3,974	,506
	Level 4 vs. Level 5	19483929542,677	1	19483929542,677	74,364	,000	,426	74,364	1,000
	Level 5 vs. Level 6	109564693,148	1	109564693,148	1,150	,286	,011	1,150	,186
	Level 6 vs. Level 7	49792363772,781	1	49792363772,781	74,717	,000	,428	74,717	1,000
	Level 7 vs. Level 8	43616704272,361	1	43616704272,361	57,302	,000	,364	57,302	1,000
	Level 8 vs. Level 9	53048130,133	1	53048130,133	,649	,422	,006	,649	,125

a. Computed using alpha = ,05

Task-Levels: 1 = Task 2, ..., 7 = Task 8

Representation-Levels: 1 = R 0, ..., 9 = R 8

Appendix III

Toolkit architecture

To develop the toolkit, we used GIT as a version control system. Since several people are working on this project, we also used Bitbucket (a GIT-based repository hosting service that allows private repositories). This service permits us to provide copies of the project codes (branches) to enable a simultaneous development process and to further manage code provisions. Accordingly, if somebody needs a copy of the code, a development group (ETHZPLUS) administrator must grant access. That user can then access and clone the source code from the following URL: https://bitbucket.org/ethzplus/landscapeization.git.

The following technical description (Figure A1) relates to the four modules of the LANDSCAPEization toolkit. These functions are described in Chapter VI.

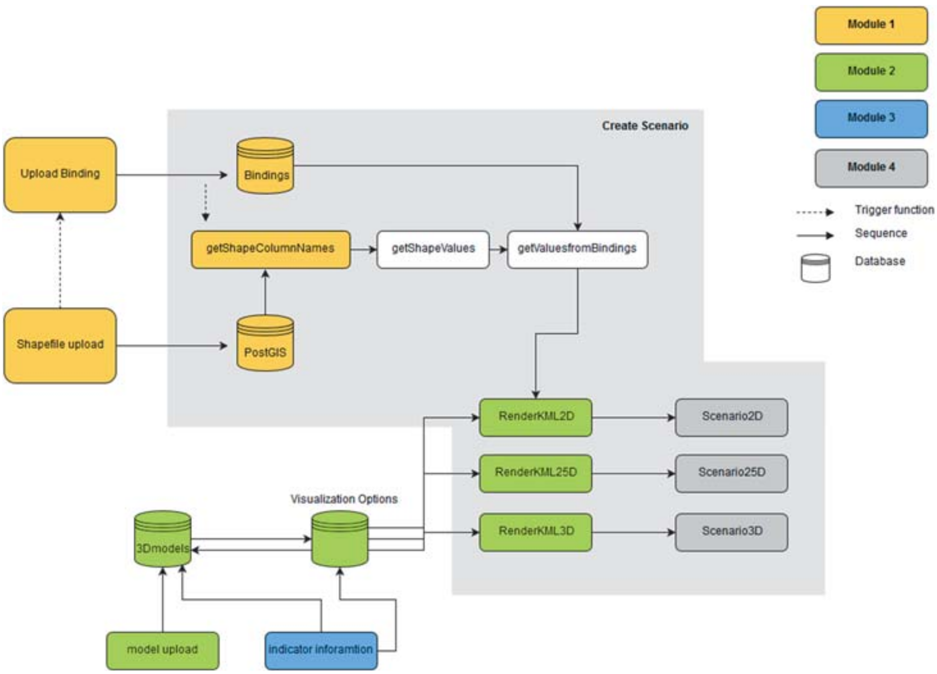


Figure A1 – Flow graph of module-based architecture

Module 1: Linking land use patterns

This module allows users to upload spatial data sets that describe land use patterns. The data sets, based on the vector file format (shapefiles), must contain spatial attributes that define land use types. After the user has uploaded a shapefile, he or she is prompted to select the attribute that defines the land use type and that he or she wants to visualize (Module 2). After selecting this attribute, the list with the different values of the selected attribute (land use types) is displayed. Following this selection, the user is forwarded to the Module 2 settings. He or she then defines each land use type (attribute value) and the required visual type (2D, 2.5D or 3D).

For example: The user uploads a shapefile with the attribute "gid" that contains different values for the polygon shapes. The platform then displays a list of "gid" values. The user clicks on the attribute values (land use type). He or she can either select (and therefore link) existing visualization options or define new visualization options for the selected attribute value (land use type) from the attribute "gid." In doing so, he or she then proceeds to select something like "gid:1 - mixed forest type A"; "gid: 2 - wheat field"; or "create new visualization type."

Module 2: Define visualization types and point cloud data

Point cloud import

The point cloud visualization script is not yet fully implemented in LANDSCAPEization, as it is not clear yet in what format the point cloud data of the first project case study region will be provided. To fully implement the import function for the point cloud data, a converting script must be implemented (depending on data format) to convert the provided data into a CSV format. However, the script for visualizing point cloud data is available and is working. The script reads a CSV file in the form of X (latitude), Y (longitude), Z (altitude), R (red color value), G (green color value) and B (blue color value). These data are then converted into KML data. The KML data are split into multiple KML 3D tiles (cubes) to reduce the file size of each KML file, enabling fast-loading performance. Furthermore, out of the data-provided coordinates and color information, a small tetrahedron is created to visualize all data.

Generic visualization options

To visualize the uploaded land use pattern data sets, visual options for 2D, 2.5D and 3D representation types are provided. The user can either define options just for a single representation type or define all representation type options for a land use type (attribute value; see Module 1). The latter allows the user to switch between the different visualization options while applying the end-user display (Module 4: front-end).

2D: Users can define a color or upload/link an image texture pattern (PNG format) to represent the land use type. For the image texture pattern, the user can define the scale so that the images can be resized to create a realistic display. This enables users to generate thematic 2D map representations (using color values) or artificial aerial images out of the linked land use pattern data sets.

2.5D: Users can define a color or upload/link an image texture pattern (PNG format) to represent a land use type. For the image texture pattern, the user can define the scale so that the images can be resized to create a realistic display. Compared to the 2D representation options, the 2.5D option further allows the user to define an extrusion height for the polygons. This extrusion height could be either set by a manual value or defined by selecting an attribute value out of the uploaded data set, which represents a specific value for each polygon. With this option, users can display the land use patterns as statistical 3D map representations or abstract 3D landscape visualizations.

3D: Identical to the 2D and 2.5D option, users can define an image texture (PNG format) as a ground texture. Additionally, with this visualization option, users can upload 3D object models (COLLADA format). These 3D object models can then be added to 3D layers that define combinations of different 3D models by density and position parameters, representing land use types. The defined 3D layers can be linked again to the attribute values of the uploaded land use patterns (land use types; see Module 1). The parameter options for density and position settings are described as follows:

- The density parameter for each 3D object model on the 3D layers can be defined by the amount per hectare by entering the value.
- The position characteristics of the 3D models within the 3D layers can be defined by a regular, random or patterned style.

Regular: With this style, the 3D objects will be positioned with the same distance between each object based on the density value. The additional positioning style also includes a random function to position 3D objects on this regular grid. With this positioning characteristic, for example, plantations can be easily represented.

Random: The random positioning style is based on the regular positioning style, but with the added functionality to randomly move the 3D model away from the regular grid by a definable range (distance in meters). The script also randomly picks the distance value, which is set according to the defined value range. With this setting's options for the random positioning of 3D models, a land use type (a forest, for example) can be easily depicted using 3D objects to simulate the natural allocation of trees.

Pattern: Users can upload a grey-scale map (PNG format) to use as a positioning pattern for the linked 3D models. Instead of setting positioning parameters as in the regular and random positioning styles, here users can manipulate an image pattern to set positioning. The black value in the image pattern describes 100% density, whereas the white value describes the 0% density of the linked 3D layers based on defined density values (amount per hectare). Additionally, the grey-scale map can be resized to define a realistic allocation of land use elements (3D models).

The 3D layers can be arranged independently of each other or in a common “shared” way to create a mix of 3D models. To do so, the user defines the same settings as the 3D layers, but for every model, he or she must select a proportion of the 3D model according to the given density. The platform then randomly chooses 3D models following the density and proportion of every point when creating the scenario.

Module 3: Add indicator information for land use type and landscape elements

The user may add indicator information either to land use definitions (indicator values per hectare) or directly to linked 3D models (indicator value per object = landscape element) in a separate menu. This data will be used later to present a reporting output via chart representation (D3.js library) according to the project configuration that the project administrator completes. Further attributes or summed spatial characteristics, like polygon areas, can also be used for this reporting output by selecting the corresponding attributes from the linked data set.

Module 4: Front end

All linked data and defined visualization and reporting outputs are accessible by a front end, which includes a graphical user interface (GUI) to navigate the landscape, control the different scenarios (attributes of linked data sets; see Module 1), switch between visualization styles (2D, 2.5D and 3D; see Module 2) and apply interactive functionalities (see Chapter VI). The front end mainframe is based on the Google Earth API, in which the generated KML of defined visualization options is displayed.

The GUI provides the following functionalities:

- Navigate, zoom, etc. through the virtual world.
- Go to the pedestrian view and return to the previous camera position.
- Switch between visualization styles (2D, 2.5D and 3D).

- Create polygons to add comments to the scenario, including indicator rankings and investigations.
- Download the scenario for offline viewing.
- Activate point cloud data to render a realistic landscape visualization in the pedestrian view.

Code-based libraries and applications

The toolkit is designed as a web application and thus utilizes client architecture and a server. The client just needs to use a standard web browser (e.g., Mozilla Firefox) that supports the Google Earth API to enable the rendering of the defined visualization options. Further, the administrator's toolkit GUI permits the manual download of defined scenarios. This permits the use of Google Earth's stand-alone tool to access visualized land use patterns.

The app is made using HTML5, CSS and JavaScript. We use the JavaScript libraries JQuery (https://jquery.com/) and D3.js (https://d3js.org/) for the reporting charts.

The server runs on a Linux box with Ubuntu 14.04 using nginx as the HTTP reverse proxy server. The server itself is written in JavaScript for Node.is (https://nodejs.org/)—a runtime environment based in V8 (the Google Chrome JavaScript engine). Hence, the entire platform's language is unified (JavaScript).

The platform uses two different kinds of databases: MongoDB to keep the browser sessions, and PostgreSQL with the PostGIS extension to store all platform data (i.e., shape files, definitions, scenarios and indicators).

Some important libraries that are required in the system are GDAL (Geospatial Data Abstraction Library), to work with shape files, and Graphicsmagick (http://www.graphicsmagick.org/), for tasks like 2D texture tiling.

Many libraries are included in the server code. The most important are:

- Express (the HTTP module for node.js)
- Iibxml (to create the scenarios' KML files)
- Bcrypt (to store passwords)
- Jade (to allow templates and to create customized HTML pages efficiently)
- Async (to more easily manage asynchronous functions)

- Zip (to compress KML files and create smaller KMZ files)

Code Snippets:

Landscapeization is basically a HTTP-based RESTful API. The server expects the following POST requests:

/uploadShapefile { shapeFile: FILE, epsg: number} ->

If (unsupportedShapeFileFormat(shapeFile)) sendError

else if (epsg= 4326) storeInSpatialDB else if (!epsg)

If (convertedEpsg) storeInSpatialDB // try to convrrt epsg to 4326 automatically else sendError

/uploadDefinition { definitionName:string, color2d: string, textureFile: FILE, textureWidth:number, textureHeight: number, textureWhole: boolean, 3dlayers: [modelName: string, deployment: string, positioning:string, density: number, patternFile:FILE, patternWidth: number, patternHeight: number, patternWhole:boolean]}

StoreTextureInDisk(textureFile)

storeDefinition2DInDB(definitionName, color2d, textureFileName, textureWidth, textureHeight,textureWhole) for 3dlayer in 3dlayers : storedefinition3DInDB(definitionName, 3dlayer)

/uploadModel {modelName, modelFile} if (unsupportedModelFileFormat(modelFile) sendError

else storeModelInDisk(modelFile)

storeModelInfoInDB(modelFile)

/uploadIndicator {elementName:string, indicatorName:string, indicatorValue:string} elementType = findElementType(elementName) // can be a visual definition or a 3d model if (!elementType) sendError

else storeIndicatorValue(elementType, elementName, indicatorName, indicatorValue)

/*

uploadBinding

This request will generate an scenario. Every scenario consists of 3 different KML's: 2d, 2.5d and 3d

Parameters:

ShapeFileName: the shape that will be used to generate the scenario

prop_name: the shape file attribute used to link its different values to visual definitions.

bindings: a list of key,value pairs in the form attributeValue: visualizationDefiniton

live: option to not create the the KML files, but instead just store the bindings to further create the scenario on the fly (this is useful when an scenario has a lot of 3d models. This could slow down the browser,or even crash the GE plugin

*/

/uploadBinding {scenarioName:strign, shapeFileName: string, prop_name: string, bindings: JSON, live:boolean}

createScenario(shapeFileName, prop_name, bindimgs, live)

The most important functions are explained below:

function **createScenario**:

storeScenarioDefinitionInDB(shapeFileName, prop_name, bindings, live)

jade_objects ={} // object to store information about every polygon in the shapefile

If (live =FALSE) jade_objects += getShapeColumnNamesFromDB(shapeFileName) jade_objects += getShapeValuesFromDB(shapeFileName) jade_objects += getValuesFromBindings(bindings)

renderKML_All(jade_objects, kmlstyles, report, scenario, bindings, shapename function **renderKML_All**(jade_objects, kmlstyles, report, scenario, bindings, shapename) renderKML2D(jade_objects, kmlstyles, scenario, bindings) renderKML25D(jade_objects, report, scenario, bindings, shapename)

renderKML3D({ jade_objects: jade_objects, report: report, scenario: scenario, bindings:

bindings, callback: cb})

function **renderKML2D**(jade_objects) kml = renderJadeTemplate2D // uses jade library

function **renderKML25D**(jade_objects)

for current_object in jade_objects: var image = { file: current_object.texture_file, width: current_object.texture_width,

height: current_object.texture_height, }

var geometry = { pg_schema: pg_schema, shapename: shapename, gid:

current_object.gid, boundary: current_object.boundary.coordinates[0], }

applyImageToGeometry(image, geometry)

// graphicksmagick to tile the image as many times as neccessary

// gdal to georeference the image in the map

// postgis functions to intersect the image with the geometry of the shapefile

createTiledKML(KML25D) uses image

// gdal utility to create a tiled KML with the same resolution as the original texture file, while improving the speed by loading just the needed tiles when neccessary. Not the whole image at once

kml = renderJadeTemplate25D // uses jade library function **renderKML3D**(jade_objects)

for object in jade_objects:

for point in object: if (groupModelDefinition) pickRandomModel

else pickDefinedModel

kml = renderJadeTemplate3D

kmz = compress(kml)

function **getValuesFromBindings**(bindings, DBinfo)

queryTable2D() // get color_2d,height,texture_file,texture_width,texture_height queryTable3D // get for every3d layer: model, density, deployment, random_oriented,

pattern_file, pattern_width, pattern_height, pattern_whole

for 3dlayer in 3dlayers: if (deployment = 'pattern') createPatterned3D(obj, density, deployment, pattern)

else getPointsInsidePolygon(KMLgeometry, boundary || [], area, density,

deployment)

createBasicReporting()

function **createPatterned3D** applyImageToGeometry(image, geometry)}, // make pattern as big as real geometry vectorizeImage // gdal insertSHPInDB // postGIS for every subpolygon created: pointsInsidePolygon()

function **pointsInsidePolygon**(geometry, boundary, area, density, deployment) if (deployment == 'regular') var grid_density = density;

else if ((deployment == 'random') || (deployment == 'random_displaced')) var grid_density = random_grid_elements_per_ha;

var x_divs = getDistanceFromLatLonInMeters(boundary[3], boundary[4]) * Math.sqrt(grid_density) / 100 ;

var y_divs = getDistanceFromLatLonInMeters(boundary[0], boundary[1]) * Math.sqrt(grid_density) / 100 ;

var diff_x = boundary[2][0] - boundary[0][0]; var diff_y = boundary[2][1] - boundary[0][1]; var step_x = diff_x / x_divs;

var step_y = diff_y / y_divs;

var points_grid = []; // total points given density in the bounding box var points_inside = []; // total points given density in the bounding box var p1 = boundary[0].slice();

for (var i=0; i<x_divs; i++){ p1[1] = boundary[0][1]; for (var j=0; j<y_divs; j++){

points_grid.push(p1.slice()); // deep array copy p1[1] += step_y; } p1[0] += step_x;

}

if (do_log) Log('pointsInsidePolygon: Started testing ST_Contains on geometry.

Total grid points to test: '+points_grid.length);

async.eachLimit(points_grid, config.async_limit_testpoints || 0 , function (point, callback_ST_contains){

myQuery('SELECT

ST_Contains(ST_GeomFromKML(\''+geometry+'\'),ST_GeomFromText(\'POINT('

+point.join(' ')+')\',4326))', false, function(err,rows){

if (rows && rows[0].st_contains == true){ points_inside.push(point.slice());

} callback_ST_contains(err); }); },function(err){ if (err){ Log('pointsInsidePolygon: Error testing points inside

polygon'); return callback(err); }

if ((deployment == 'random') || (deployment ==

'random_displaced')){ //have to remove points from the array var n_models = Math.round(density * area / 10000); Log('Deployment: '+deployment+': total models to place:

'+n_models+ '. Total points inside: '+ points_inside.length);

while(points_inside.length > n_models){ var random_index = Math.floor(Math.random() *

points_inside.length); points_inside.splice(random_index,1); } }   if (deployment == 'random_displaced'){ for (var i=0; i<points_inside.length; i++) { var point = points_inside[i];

var displ_x = Math.random()* 2 * random_displaced_max_distance_deg - random_displaced_max_distance_deg;   var displ_y = Math.random()* 2 * random_displaced_max_distance_deg - random_displaced_max_distance_deg; point[0] +=

displ_x; point[1] += displ_y; } } if (do_log)

Log('pointsInsidePolygon: Finished testing ST_Contains for polygon. Points inside: '+points_inside.length);

//Log('Finished testing ST_Contains for polygon GID:'+gid+'. Points inside: '+points_inside.length); callback(null,points_inside); });

Declaration

I hereby declare that this cumulative Ph.D. thesis is the result of my personal scientific contributions. I have played the leading role in all substantial contributions, from conception to design, development and analysis of the theoretical models and tools, as well in the acquisition of data, analysis and interpretation of data of all first authorship publications (Paper I, II, III; Appendices B, D). Further, the conception, design and realization of the described visualization techniques in the two co-authorship publications were undertaken in most (Appendix A) or some parts (Appendix C) by me in person. Therefore, the publications contained in this thesis reflect my intellectual contributions to the before-mentioned projects.

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Many thanks!

Curriculum vitae

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Born:	October 5th, 1982, Bad Mergentheim (Germany)
Nationality:	German

Academic Education

2013 – 2016	Doctoral studies, ETH Zurich, Department of Civil, Environmental and Geomatic Engineering, Switzerland
2013 – 2014	Certificate of Advance Study - CAS "Spatial Information Systems", ETH Zurich, Institute of Cartography and Geoinformation, Switzerland
2004 – 2010	Dipl. Geogr. (M. Sc.), Emphasis: Physical Geography - Environmental processes and natural hazards, Katholische Universität of Eichstätt-Ingolstadt, Germany Thesis: Surface roughness determination using LiDAR (Terrestrial and Airborne Laserscanning) - Analysis of rockfall deposits
2007 – 2010	Minor field of study in Photogrammetry and Remote Sensing, Technische Universtität München, Institute of Photogrammetry and Cartography, Germany
2004 – 2010	Minor field of study in Journalism & Communication Science, Katholische Universität of Eichstätt-Ingolstadt, Germany
2004 – 2007	Minor field of study in Sociology, Katholische Universität of Eichstätt-Ingolstadt, Germany

Professional Experience

2013 – 2016	Research associate and Ph.D. student, ETH Zurich, Institute for Spatial and Landscape Planning (IRL), Planning of Landscape and Urban Systems (PLUS), Switzerland
2010 – 2013	Build-up and coordination of Landscape Visualization & Modeling Lab (LVML), ETH Zurich, Institute for Spatial and Landscape Planning (IRL), Planning of Landscape and Urban Systems (PLUS), Switzerland

2007 – 2010	Technical assistant at Faculty of Mathematics and Geography, Chair of Physical Geography, Katholische Universität of Eichstätt-Ingolstadt, Germany
2007 – 2010	Research assistant at Faculty of Mathematics and Geography, Chair of Physical Geography, Katholische Universität of Eichstätt-Ingolstadt, Germany Project: DFG-Project: High-resolution quantification and modeling of rockfall processes on Alpine cliffs using survey data of terrestrial laser scanning and digital photogrammetry
2007	Internship at German Aerospace Center (DLR), GeoVisualisation Center of German Remote Sensing Data Center (DFD), Oberpfaffenhofen, Germany
2007	Internship at Department of GeoInformation (GeoInformationsdienst der Bundeswehr), German Federal Armed Forces, Euskirchen, Germany

Publications

2016

Grassi, S., Klein, T. M. (2016): 3D augmented reality for improving social acceptance and public participation of wind farms. In: Journal of Physics: Conference Series, Volume 749, Number 1.

Klein, T. M., Grêt-Regamey, A. (2016): Developing an ecosystem services information tool: A workflow applying requirements engineering approaches. In: Book of abstracts of session: C8 - Guidance for users on Ecosystem Services, 8th Conference of the Ecosystem Service Partnership in Antwerp, Belgium September 19-23th, 2016.

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2015

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2014

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2013 Klein, T. M., Grêt-Regamey, A. (2013): Web-Based Decision Support System - Visualization & Communication of Ecosystem Services, OPERAs meeting, October 16-18th 2013, Palma de Mallorca, Spain.

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2012 Grêt-Regamey, A., Celio, E., Klein, T.M. (2012): Zukunftsvisionen entschlüsseln, um heute Entscheidungen zu treffen! Interaktives 3D Visualisierungstool verbindet Ursachen und Wirkung der Landschaftsentwicklung und wird an der AlpenWoche 2012 getestet. In: Forum.Landschaft - Infoletter, p.4-5, 08/2012.

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2011

Altwegg, J., Klein, T. (2011): Einblick in Methoden und Erfassungsinstrumente des LFI sowie mögliche zukünftige Instrumente für die Waldinventur - Auswertemöglichkeiten der Datenerfassung mit neuen Aufnahmetechniken Laserscanning und Drohne. Jahrestagung der Arbeitsgruppe Waldplanung und -Planung, Schweizerischer Forstverein.

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2010

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Research project involvement

- Operational Potential of Ecosystem Research Applications (www.operas-project.eu)
- Sustainable Use of Soil as a Resource (OPSOL) - National Research Programme NRP68 (www.nfp68.ch)
- 3D GIS zur Planung elektronischen Versorgungsnetzen (http://netzausbau.ethz.ch)
- Invasive Plant Visualizations for Decision Support for Measure Program (www.plus.ethz.ch/research/neophyt)
- Visualisierungs-Plattform für die Bewertung von Siedlungsszenarien der Gemeinde Worb
- Mountland2: Prioritization for adaption to climate and socio-economic changes (www.wsl.ch/mountland)
- SNF project: VisAsim – Visual-Acoustic Simulation for landscape impact assessment of wind farms (www.VisAsim.ethz.ch)
- Interatkive 3D Visualisierungen zur Kommunikation in Meliorationsprozessen - Fallstudie Brislach (BL)
- Entwicklung einer Visualisierungsplattform für den Gewässerraum: Web-GIS Implementierung (www.gr-vis.ethz.ch)
- 3D visualization of alternative landscape development scenarios for public participation and informed decision making - case study of Blauen (BL)

Supervision of master thesis

- Song, J. (2016): Decision support system for sustainable power line planning: usability and user experience design research
- Bauer, L. (2015): Visualisierung und Kommunikation der Auswirkung neophyter Pflanzenarten
- Kälin, P. (2015): Augmented Reality zur Visualisierung und Kommunikation räumlicher Qualitäten
- Bernet, A. (2013): The impact of spatial patterns of buildings on the local airflow in a megacity and suitable assessment methods. A case study of Kampung Melayu, Jakarta
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- Hürlimann, N. (2012): Interaktive GIS-basierte prozedurale Visualisierung und verlinkte Indikatoren zur Veranschaulichung und Bewertung von Alternativen der Siedlungsverdichtung.

- Manyoky, M. (2011): SoundLandScape - Linking GIS-based 3D landscape visualization and spatial explicit ambient noise made by wind turbines.
- Glaus, M. (2011): 3D Visualisierung verschiedener Landschaftsentwicklungsoptionen als Medium zum Dialog mit der Bevölkerung und zur informierten Entscheidungsfindung - Fallbeispiel Blauen (BL)
- Weber, R. (2011): Darstellung von Konzepten in 3D-Visualisierungen am Beispiel Raumkonzept Schweiz.

Teaching experience

- *LVML 1: Interdisciplinary tools for landscape architecture and planning* at ETH Zurich, Institute for Spatial and Landscape Planning (IRL), Planning of Landscape and Urban Systems (PLUS), Switzerland
- *LVML 2: GIS-based 3D Landscapes for Participative Planning* at ETH Zurich, Institute for Spatial and Landscape Planning (IRL), Planning of Landscape and Urban Systems (PLUS), Switzerland
- *Planning III* at ETH Zurich, Institute for Spatial and Landscape Planning (IRL), Planning of Landscape and Urban Systems (PLUS), Switzerland