ENHANCEMENT OF DECISION-MAKING IN COMPLEX ORGANIZATIONS: A SYSTEMS ENGINEERING APPROACH
Shqipe Buzuku

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Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1316 at Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland, on the 22nd of March, 2019, at noon.

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Abstract

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Effective methods to identify and model design processes are important for understanding organizational complexity. With this purpose, several modeling techniques for the design and development of decision-making processes have been developed over the years, grounded on different backgrounds and considering different perspectives. Moreover, decision-making methods can be applied as techniques to assist in the design process.

The aim of this study is to propose a framework for the development of a methodology and tools to enhance the decision-making process in complex organizations. The framework consists in a systems engineering approach by combining both creative and analytical methods, such as morphological analysis, sensitivity analysis, design structure matrix, Boolean logic and ranking methodology.

The findings show that a systematic approach is an appropriate tool to structure and manage different design activities. Furthermore, it helps to improve decision-making among engineers, planners and designers by providing a basis for communication and learning across domains with high impact in eco-design practices. The systematic approach is tested and refined in case studies involving cross-functional inter-organizational groups of expert participants in the eco-design policy formulation and implementation.

This dissertation contributes on enhancement of the decision-making process by structuring and managing design activities in complex technical organizations. First, the study aims at recognizing the connection between the engineering systems’ requirements and project management activities. By incorporating multiple design dimensions and categories, new co-creation opportunities are highlighted and their requirements can be consolidated and optimized. Second, the research extends the application of creative design approach, specifically within a set of activities.

The study recognizes and analyses the conflicts between different design activities and aims at creating alternative options and sustainable solutions to resolve these conflicts.
The research has been carried out in cooperation with the Finnish pulp and paper industry, and the results have been validated only within this scope.

**Keywords:** process design, complex systems, design activities, decision-making, systematic approach, systems engineering, engineering management, organization.
Acknowledgements

The research journey of completing this doctoral dissertation was a long process and a challenging task. This was a challenge because of frustration, which ultimately led to self-development, which in turn helped me to build up my character and achieve something that I could only dream about. The beauty of this process is that I met many great and friendly people, intelligent and brilliant researchers from different parts of the globe, which will forever remain the best part of this journey. This achievement was possible because of the tremendous support from the following people.

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Shqipe Buzuku
March 2019
Lappeenranta, Finland
“I just proved to the world that even after the war, even after we survived a war, if Kosovars want something they can have it. If they want to be Olympic Champions, they can be”

-Judo World Champion Majlinda Kelmendi wins Kosovo’s first ever Olympic gold medal.


This thesis is dedicated with full of love to my beloved parents,
Nezir Buzuku and Bahtie Buzuku
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PUBLICATION I:


The author was responsible for the research plan, data collection, finding analysis and implementation. Overall, the paper was written in cooperation with the co-author and the main author coordinated the research and writing of the paper. The paper was accepted for publication in the journal based on double-blind review.

PUBLICATION II:


The author was responsible for the research plan, and had primary responsibility for collecting the data, analyzing the findings and drawing conclusions. Second author facilitated the data collection and the paper was written in coordination with both co-authors. The paper was accepted for conference proceedings following a double-blind review.

PUBLICATION III:


The author was responsible for the research plan, and had primary responsibility for collecting the data, analyzing the findings and drawing conclusions. The third co-author was involved in the data analysis. The paper was written in coordination with
both co-authors. The paper was accepted for conference proceedings following a double-blind review.

PUBLICATION IV:


The author was responsible for the research plan, data collection and implementation. Overall, the paper was written jointly with the second author and in cooperation with other co-authors. The third co-author facilitated data collection and second author was involved in the data analysis. The paper was accepted for publication in the journal based on double-blind peer review.

PUBLICATION V:


The author was responsible for the research plan, data collection, data analysis and implementation. The paper was written in cooperation with the co-author. The paper was accepted for a book chapter following double-blind peer review.

PUBLICATION VI:


The author of this thesis drew up a research plan and conducted the research interviews and data collection, analyzing the findings and drawing conclusions. The second author was involved in the data analysis and findings. The paper was written jointly with the second author and the main author took primary responsibility for revising the paper during the review process. The paper was accepted for the publication in the journal based on double-blind peer review.

The Finnish Publication Forum JUFO (*Julkaisufoorumi*) is a system of publishing channels categorization for assessing the quality of scientific research. The score level varies from 0 to 3, where “0” is the lowest and “3” is the highest value.
List of other publications


## List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CCA</td>
<td>Cross-Consistency Assessment</td>
</tr>
<tr>
<td>DDP</td>
<td>Design Dependent Parameters</td>
</tr>
<tr>
<td>DIP</td>
<td>Design-Independent Parameters</td>
</tr>
<tr>
<td>DMM</td>
<td>Domain Mapping Matrix</td>
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<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DSM</td>
<td>Design Structure Matrix</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision Support Systems</td>
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<tr>
<td>GMA</td>
<td>General Morphological Analysis</td>
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<tr>
<td>INCOSE</td>
<td>International Council on Systems Engineering</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LUT</td>
<td>Lappeenranta University of Technology</td>
</tr>
<tr>
<td>MA</td>
<td>Morphological Analysis</td>
</tr>
<tr>
<td>MCDM</td>
<td>Multi-Criteria Decision-Making</td>
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<tr>
<td>MDM</td>
<td>Multi Domain Matrix</td>
</tr>
<tr>
<td>NATO</td>
<td>North Atlantic Treaty Organization</td>
</tr>
<tr>
<td>OPEC</td>
<td>Organization of the Petroleum Exporting Countries</td>
</tr>
<tr>
<td>RDA</td>
<td>Research Design Activities</td>
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<tr>
<td>SA</td>
<td>Sensitivity Analysis</td>
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<tr>
<td>SE</td>
<td>Systems Engineering</td>
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<tr>
<td>UN</td>
<td>United Nations</td>
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<tr>
<td>WWTP</td>
<td>Wastewater Treatment Plant</td>
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PART I: OVERVIEW OF THE DISSERTATION
1 Introduction

1.1 Background

We are living in a world where our systems are becoming often increasingly complex (Eppinger and Browning, 2012; Steward, 1981a). Activities as a whole may be perceived simpler, despite the increased complexity of the system. A good example of this is sending a message: nowadays we can communicate large amounts of information in an instant from a small device in our pockets. This is a huge improvement and simplification of an activity that used to take days at best in regular hand-written post. However, the system itself is unbelievably more complex: the amount of physics and technological advances required for this, as well as the robust wireless communication infrastructure results in a system that is terribly complex, yet paradoxically, makes our lives easier.

As a consequence of increasing complexity, wicked problems arise in organization systems (Ritchey, 2010; Rittel and Webber, 1973). As the problems of the world become increasingly complex, the consequences of our decisions are more and more difficult to predict. To catch up with the complexification, our decision-making processes have to evolve (Bennet and Bennet, 2008). An organization is a complex cluster of interdependent and interrelated structures and activities, with the purpose of to maximizing the gains of individuals and the organization as a whole (Janczak, 2005). As Thompson (1967) points out, “the complex organization is a set of independent parts, which together make up a whole in that each contributes something and receives something from the whole, which in turn is interdependent with some larger environment”.

Furthermore, complexity in organization systems is escalating because systems involve an increasing number of people, companies, governments and existing technologies (Luo and Wood, 2017) and extending to a wide range of disciplines including products, processes, organizations, projects and environment (Eppinger and Browning, 2012). Complexity in organization systems is prone to create a challenging environment for research and development activities, increasing the cost, time and risk to new and ongoing projects (Allaire et al., 2012; Bearden, 2003). Complexity in organization systems is a key factor in the inability or inefficiency of design efforts to succeed. Therefore, the need of approaches for handling and mitigating the complexity of the examined organization systems exists (Piccolo et al., 2018). Moreover, the increasing complexity is also a trend in engineering systems (Bartolomei et al., 2012), design and planning processes in organizations (Eppinger and Ulrich, 2015; Pimmiller and Eppinger, 1994).

Commonly, the business goals of some complex organizations are achieved by implementation of research design activities (RDA) in cross-functional and inter-organizational teams (Pettersson and Lundberg, 2018). Design, structuring and managing complex design activities is challenging, because decision-making involves a considerable amount of stakeholders and possible activities (Parraguez et al., 2016, 2015; Piccolo et al., 2018). As defined by Bahill and Gissing (1998), a part of systems
engineering is design. Design is, in a way, a problem solving exercise, where complex situations and decision-making meet.

Parraguez et al. (2016) defines the engineering design process as a concept sustained by three “pillars”: the process domain (comprised of the process activities), the organizational domain (comprised of the human capital carrying out the activities) and a product domain (constituted by the physical components used or produced during the process). In addition, Parraguez et al. (2016) proposed a novel systematic method to characterize process interfaces in the way of organization networks, constituted of the interactions between activities and people in the context of development of a power plant. Moreover in the engineering design processes, problems are usually made further complex because they require effort from several individuals performing various activities aiming to reach the common organization goal (Eppinger and Ulrich, 2015; Piccolo et al., 2018). As a result, activities are sometimes formulated with contradictory requirements.

According to The Royal Academy of Engineering and Centre for Real-World Learning, engineering identifies six engineering habits as following: problem finding, creative problem solving, visualizing, systems thinking, improving and adapting (Lucal et al., 2017; Yasseri, 2017). In brief, systems thinking is the perception and understanding of the system as a whole but also as a collective of parts and their interactions. Problem finding refers to the identification of needs and understanding the requirements and contexts. Visualizing refers to the ability to shift from the abstract to the concrete. Improving refers to the continuous effort to better something through constantly testing, experimenting and applying the improvements. Creative problem solving refers to the application of untraditional approaches (or traditional approaches in untraditional ways) to reach new solutions and ideas. Finally, Adapting refers to the exercise of methodological flexibility, where through analysis, testing and reflection it is made possible to meet new challenges using known techniques in new ways, or learning new techniques altogether.

Engineering is also tightly related to science and research. While science focuses on the study of the physical world, engineering uses the generated scientific knowledge to design devices, structures or processes (Blanchard and Fabrycky, 2013; Boardman, 1990). Engineering science, thus, resides in the middle, where the process, device or structure under design serves an experimental purpose (Boardman, 1990; Martin, 1996).

Rather important parts of design are modeling and optimization, which are crucial aspects in the design process, leading to a pathway for effective solution in complex systems (Matasniemi, 2008). In other words, models allow decision-makers to separate complexity from the real world, so the analysis of the most relevant parts of the system become the focus (Sterman, 2002). Modeling complex systems has the potential to produce valuable insights about their behavior and structure, thus increasing the decision-makers’ understanding and capacity to manage systems (Eppinger and Browning, 2012).
1.2 Motivation of the study and scope

Currently, models are experiencing a continuous transition, often motivated by the need to address complex problems in organizations. As described by Janczak (2005), “Organizations are associations of persons grouped together around the pursuit the specific goals”. Good examples of complex organizations are The North Atlantic Treaty Organization (NATO) and the United Nations (UN), because they are comprised of multiple levels of hierarchy and thousands of units and millions of elements. Consequently, higher hierarchical levels are often exposed to higher levels of complexity (Bartolomei et al., 2012). As a result, actors (decision makers, engineers, designers, etc.) often do not entirely understand the elements of the system they have to work with (O’Donovan et al., 2004). Therefore, the decision-making process is difficult to perform and manage efficiently when different levels of complexity are dealt with.

Because the design activities and development of methods and patterns are vital to the organizations’ performance, this motivates further research to improve the understanding of processes and how to support them (Parraguez et al., 2016; Wynn and Clarkson, 2018). Research points out that a systematic approach may help to deal with the above-mentioned problems in several ways. In line with the literature, this dissertation was performed in the context Finnish pulp and paper industry, with a focus on a systematic approach.

The scope of this research is in the Finnish pulp and paper industry. All the empirical materials and data have been collected there. Also the results are only validated within this boundary. Some characteristics, which strongly reflect in the issues raised in the study, relate to the structural properties of the industry. These characteristics and issues have been the focus for data collection, analysis and questions in the research. Firstly, the pulp and paper industry is very capital-intensive industry, because the investments incurred are huge, and the lifetime of those investments is often more than 30 years. Secondly, the industry is raw materials related, thus the pulp mills require to be located in close proximity to forests. Thirdly, the heavy process industry is inevitably burdening the environment, both using the natural resources and generating emissions. The CO₂ emissions are currently a very relevant issue due to climate change, even though the pulp and paper industry as such functions on a sustainable basis, because it operates using biomass and generating emissions that the forest would release overtime in any case. Fourthly, the market of paper industry is changing rapidly, because the printed paper market is shrinking rapidly due to digitalization. Other new products are emerging to replace the traditional products, such as compostable and disposable paper cups.

The Systems Approach sets out a debate between several parties, each of whom advance their individual, distinctive approaches to the one central problem, in this case the understanding of the engineering systems which we live with (Martin, 1996; Blanchard and Fabrycky, 2013). A systematic approach showcasing the best practices might be helpful to “rationalize creative work, to reduce the likelihood of forgetting something important, to permit design to be tough and transferred, to facilitate planning, to mitigate
complexity and to improve communication between disciplines involved in design” according to Gericke and Blessing (2011).

Novel applications of systems engineering include, for example, in the area of public sector decision-making (Eppinger and Browning, 2012; Furtado et al., 2015). Decision-making problems may appear at each step of the process design, partly due to the need to deal with technical options (Clark et al., 2009). This type of problems are often linked to several (and in some cases conflicting) requirements, where a creative resolution results in good design (Blanchard and Fabrycky, 2013).

The range of the engineers’ tasks has been shifting from the regular problem-solving role (analytical) into a broader problem-framing role (normative) (Bañares-Alcántara, 2010; Taeihagh et al., 2009). Consequently, engineers and especially the systems engineers should participate in the decision-making process (Bañares-Alcántara, 2010). Moreover, the area of application of systems engineering is further broadening. For example, in the case of sustainable development, both objectives and criteria for success should be established carefully as part of the decision process.

Decision-making is often a difficult task in complex systems. Decision-making has been present at least since the beginning of management and leadership, but probably longer (Bennet and Bennet, 2008). From at least the 1990s, decision-makers became well-versed in mathematical and statistical techniques, and began to investigate the “qualitative” side of decision-making, dealing with probabilities, preferences and propensities (Bennet and Bennet, 2008). Furthermore, decision-makers are often in situation where they have to trust their gut or intuition. Therefore, this added complexity to decision-making still needs to be further studied.

Research on engineering systems, complex systems and decision-making process has been of interest for many decades a growing phenomenon due to the importance of technical and organizational complexity and social intricacy of human behavior (Bartolomei, 2007; Rouse, 2007). Engineering systems can also be socio-technical systems that provide solutions to central economic and societal challenges (Bartolomei et al., 2012). Moreover, engineering systems combine engineering with perspectives from management, economics and social science in order to address the design and development of the complex, large-scale, socio-technical systems that are so important in all aspects of modern society (Bartolomei et al., 2012). The intersection of the research fields in design, management and social sciences results as engineering systems, shown in Figure 1, and contains the focus of this dissertation.
Focus area of the research: Mitigating the complexity by structuring and managing complex design activities in complex systems

Figure 1. Positioning of the study within literature

Examples of engineering systems include generation and distribution of energy, enabling global communication, creating affordable healthcare, managing global manufacturing and supply chains or building and maintaining critical infrastructure (ESD, 2008).

These systems have the following things in common: they are complex technically and organizationally are affected by the social aspects of human behavior, and experience a certain level of uncertainty over the span of their operation. In order to address these challenges, an interdisciplinary approach is needed. The approach must target the three major research fields: Social Science, Management of Engineering Systems and Design of Engineering Systems (Bartolomei et al., 2012).

Thus, complexity is generated at the point of interaction or interrelation of elements within a system, and also with elements from the environment of the system (Bennet and Bennet, 2008). According to Bennet and Bennet (2004), complexity is a condition or situation of a system that depends on too many variables and relationships, so it cannot be analyzed or understood by simple analytic methods. Within this context, the problems or situation requiring a decision are “likely to be unique, dynamic, unprecedented, and difficult to define or bound, and have no clear set of solutions” (Bennet and Bennet, 2008).
In modern organizations and enterprises, various complex problems are associated with people’s interactions, due to multiple teams and tasks from multidisciplinary fields (Eppinger and Browning, 2012; Pimmler and Eppinger, 1994). In the context of modern organizations, people must work together in order to solve problems (Browning et al., 2015). For solving complex problems, it is required to involve several individuals, and sometimes organizations, that can result in overlapping roles (Eppinger and Ulrich, 2015). An example of this are tasks in engineering, systems architecture, operation management, etc. involving internal communications and cross-functional, inter-organizational teams, and further possible combinations (in some cases multiple locations, languages and cultures), that currently experience rather complex environments (Bartolomei et al., 2012).

This situation highlights the need to design and develop methods and tools to deal with the large amount of information needed to understand, design and improve systems (Danilovic and Browning, 2007; Eppinger and Browning, 2012; Yassine et al., 2001). There is a vast amount of scholars, researchers and practitioners from multidiscipline focused on developing and validating design engineering methods supporting decision-making to meet the needs of industrial processes and engineering management (Mejía-Gutiérrez and Carvajal-Arango, 2017).

Systems engineering (SE) is a “rational approach to decision-making related to the solution of complex problems in engineering, planning, design and operation management” (Eppinger and Browning, 2012; Maurer, 2017). SE is an immensely practical science that also provides a unique richness of approach to problem solving, since it includes a great variety of design tools and techniques, coupled with a wealth of decision-making methods (Bartolomei et al., 2012; Blanchard and Fabrycky, 2013). However, decision-making process remains a challenging task for managing complex design activities in organizations (Danilovic and Browning, 2007; Flüeler, 2006). Furthermore, there are several research questions yet to be answered, creating gaps in knowledge regarding complex systems, structuring and modeling design activities (Parraguez et al., 2015) and underlying human behavioral mechanisms of decision-making (Blanchard and Fabrycky, 2013).

This leads to the proposition of using the existing methods from a different perspective, by integrating a systematic approach to enhance the decision-making process in complex organizations. The set of methods used in this dissertation are represented in Figure 2, including creative method (Morphological Analysis), analytical and engineering method (Design Structure Matrix), mathematical method (Boolean and Sensitivity Analysis), and decision method (Multi-Criteria Decision-Making) – all together comprise a systematic approach. Each publication applies one or more methods, which consists in a systematic engineering approach as shown in Figure 2.
1.4 Purpose of the study, objectives and research questions

The purpose of this PhD dissertation is to create a framework for the design and development of a methodology and tools for improving the decision-making process. The target has been structuring and managing complex design activities for sustainable management in organizations. More specifically, the framework consists in the development of a systematic approach for the effective formulation and implementation of engineering design activities for improving the decision-making process in complex organizations.

Thus, this dissertation is focused on two main research objectives that constitute the contribution of the study to existing knowledge:

1. To identify and analyze key challenges and obstacles hampering engineering design activities and strategies in complex organizations.
2. To develop and implement a methodology for modeling and managing engineering design activities that enhance decision-making process in complex organizations.

Furthermore, this research project outlines a systematic approach for complex problem solving and continuous improvement of the decision-making process in the context of the Finnish pulp and paper industry.

The dissertation work presents a model to support the decision-making process by shedding light on the use of systems models to cope with the integration of sustainable concerns into strategic problems. Traditional multi-objective approaches often are not sufficient to deal with the multi-dimensional and often non-quantifiable characteristics of the problems under analysis. This dissertation addresses the main research question as following: What is the mechanism to improve decision-making in complex technical organizations?

This dissertation addresses this question by researching several decision-making methods in an organizational setting, and investigates their repercussions into different organizational goals to ensure quality of the systematic decision-making.

Thus, this dissertation attempts to answer the following research sub-questions.

Q1. Can MA, DSM and MCDM-Ranking be used in decision-making for eco-design implementation in the Finnish pulp and paper industry? (Publication I, II, III, IV, V, VI)

Q2. Can DSM be further enhanced to improve the decision-making process in different sectors for eco-design implementation in the Finnish pulp and paper industry? (Publication II, III, VI)

Q3. Can MA be further enhanced to improve decision-making in the Finnish pulp and paper industry? (Publication III, V, VI)

The research process of the dissertation follows four steps. First, an analysis for the formulation and identification of the elements (barriers, drivers, policy measures, etc.) and requirements for implementation of eco-design strategies in the Finnish pulp and paper industry is presented. Next, the synthesis of the design criteria, such as design-dependent parameters and design alternatives, obtained from data collected from literature research and interviews, as well as identification of viable methods are carried out. Third, design and development of a systematic approach supporting decision-making is developed for better managing and improving engineering design activities. Fourth, the evaluation and validation of the proposed approach supporting decision-making within the Finnish pulp and paper industry perspective is given.
1.5 Key definitions

In this section, a list of the key concepts and definitions used in the dissertation is presented. The list is purposefully arranged in alphabetical order in Table 1. The list is comprehensive in reach, but shallow in detail, as the detailed description of the terms is presented respectively as they appear in the dissertation work.

Table 1. Summary of definitions

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Definition</th>
<th>Source</th>
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<tbody>
<tr>
<td>Activities</td>
<td>“the elements of actions comprising a process, which in various contexts may be tasks to execute, information to generate, decision to make, or design parameters to determine”</td>
<td>(Eppinger and Browning, 2012)</td>
</tr>
<tr>
<td>Block</td>
<td>“a group of coupled activities identified in the process architecture DSM”</td>
<td>(Eppinger and Browning, 2012)</td>
</tr>
<tr>
<td>Complexity</td>
<td>“is associated with the intricate inter-twining or inter-connectivity of elements within a system and between a system and its environment”</td>
<td>(Miller and Page, 2009)</td>
</tr>
<tr>
<td>Cluster</td>
<td>“a set of components grouped because of certain relationships, suggested through analysis of the product architecture DSM, and defined to comprise a module or subsystem”</td>
<td>(Eppinger and Browning, 2012)</td>
</tr>
<tr>
<td>Design</td>
<td>“a creative decision-making process that aims to find an optimal balance of trade-offs in the production of an artefact that best satisfies customer and other stakeholder preferences”</td>
<td>(Skerlos et al., 2006)</td>
</tr>
<tr>
<td>Eco-design</td>
<td>“the systematic integration of environmental and strategic considerations into product and process design”</td>
<td>(ISO, 2011)</td>
</tr>
<tr>
<td>Interactions</td>
<td>“the relationships between components or elements in a systems. Depending on one’s point of view, a component may be a complex product or system”</td>
<td>(Eppinger and Browning, 2012)</td>
</tr>
<tr>
<td>Iteration</td>
<td>“the repletion of activities, also known as rework. Iterations may be planned (due to coupling or uncertainty) or unplanned (due to discovery to errors or arrival of new information)”</td>
<td>(Eppinger and Browning, 2012)</td>
</tr>
<tr>
<td>Model</td>
<td>“a description or analogy used to help visualize something that cannot be directly observed”</td>
<td>(Haskins, 2006)</td>
</tr>
<tr>
<td>Organization</td>
<td>“a network of people with a common purpose, such as a business unit or a project developing, producing, selling, or supporting a product”</td>
<td>(Eppinger and Browning, 2012)</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
<td>Reference</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------------------------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Policy</td>
<td>“a principle or guideline for action in a specific everyday-world context”</td>
<td>(Pohl, 2008)</td>
</tr>
<tr>
<td>Policy design</td>
<td>“a step whereby the components of a policy are selected and the overall policy formulated”</td>
<td>(Taeihagh et al., 2009)</td>
</tr>
<tr>
<td>Policy measure</td>
<td>“is the building block used for the creation of policy packages, clusters and ultimately, the future image to reach the target”</td>
<td>(Taeihagh et al., 2009)</td>
</tr>
<tr>
<td>Process</td>
<td>“a system of activities and their interactions comprising a project or business function, such as an engineering design and development project”</td>
<td>(Eppinger and Browning, 2012)</td>
</tr>
<tr>
<td>Stakeholder</td>
<td>“a person or organization who influences a system’s requirements or who is impacted by that system”</td>
<td>(Freeman et al., 2010)</td>
</tr>
<tr>
<td>Strategy</td>
<td>“...strategy is concerned with planning how an organization or an individual will achieve its goals”</td>
<td>(Grant, 2005)</td>
</tr>
<tr>
<td>System</td>
<td>“a system is nothing more than a way of looking at the world, or point of view”</td>
<td>(Weinberg, 2001); (Martin, 2007)</td>
</tr>
<tr>
<td>Systematic approach</td>
<td>“an interdisciplinary approach and means to enable the realization of successful systems”</td>
<td>(Pahl et al., 2007) (Blanchard and Fabrycky, 2013)</td>
</tr>
<tr>
<td>Theory</td>
<td>“a plausible or scientifically acceptable general principle or body of principles offered to explain phenomena”</td>
<td>(Blanchard and Fabrycky, 2013)</td>
</tr>
<tr>
<td>Wicked problem</td>
<td>“are complex, ill-structured, intractable, open-ended, unpredictable-seem to be proliferating and do not have an enumerable set of potential solutions”</td>
<td>(Rittel and Webber, 1973)</td>
</tr>
</tbody>
</table>

1.6 Outline of the research and organization of the thesis

This dissertation is constructed of two sections. Part I presents introduction and Part II presents contribution. Introduction part provides an overview of the dissertation. The contribution part includes the publications addressing the research steps introduced before, presents the research results and applies the systems engineering approach to structure and manage complex systems in organization.

The first part begins with an introduction to the study. Chapter 1 describes the background, motivation of the study and scope, research gap(s), purpose of the study main objectives and research questions. Chapter 2 presents the current academic literature review on the concept of organization as a complex system. Chapter 3 discusses the research design of the study, by summarizing the methodological choices of this work, research mixed methods including qualitative and quantitative, multiple case study with data collection and data analysis and quality of the research. Chapter 4 summarizes the key results of the individual publications included in the Part II that respond to the research steps stated in the introduction part, and covers the analysis of challenges
identified with the use of a SE approach. Finally, Chapter 5 presents the conclusions of the study by presenting key theoretical and methodological contributions, managerial implications, limitations and suggestions for future research. The outline of the thesis and output of each chapter are shown in Figure 3.
2 Theoretical background

In this section, the theoretical background of the thesis is laid out. The content focuses on three main concepts of research in which the thesis is based: enhancement of decision-making, complex organizations and systems engineering. Section 2.1 focuses on describing organizations as a complex system, section 2.2 explains further decision-making process in complex organizations, section 2.3 introduces systems engineering and the section 2.4 explains methods of problem solving used in systems engineering.

2.1 Organizations as complex systems

In order to understand why organizations are complex, it is important first to define what an organization is. According to Eppinger and Browning (2012), an organization is “a network of people with a common goal, such as a business unit or a project developing, producing, selling, or supporting a product and is linked to an external environment, and are social entities oriented to certain goals” (Fabac, 2010). Organizations are commonly identified by their elaborated structures and coordination of multiple activities, but also tend to be transparent in regard of the nearness with their context. Organizations are constituted by an array of human and material resources that perform activities together Fabac (2010). Resources are managed with the target of completing tasks, which are aligned with the organization’s goals.

A commonly used analogy to approach organizations is to address them as systems, an approach that originated in cybernetics and socio-technical complex systems (Emery, 1993). This approach focuses on finding patterns or rules of behavior of the organizations and attempts to analyze them as technical systems. From the system’s management point of view, the concepts of feedback, control, measurement of system’s performance, etc., can be applied in organizations as social systems.

A complex system is defined by Simon (1962) as “one made up of many elements that interact in a non-simple way”. Over time, the interactions of the system’s elements influence the system behavior, affecting the performance and evolution individuals, and thus the system as a whole (Arthur, 1999). Consequently, the collective behavior of the system’s elements together extends beyond the aggregation of their isolated behaviors (Anderson, 1972). Moreover, Allaire et al. (2012) defines system complexity as “the potential for a system to exhibit unexpected behaviors in the quantities of interest”. Finally, Newman (2011) summarizes that a “complex system may be briefly said to be a system of interacting parts that display emergent behaviors”.

Complexity has the potential to generate unpredictability in a systems’ behavior (always undesirable in organized systems) (Miller and Page, 2009), thus one of the aims of SE is to reduce both the unpredictability factor and the effects of it. The involvement of experts can assist with the mitigation of the unpredictable and its effect (Blanchard and Fabrycky, 2013). Therefore, a complex system by definition is a collection of several individual
entities that behave in pursuit of their objectives and experience mutual interactions, but have a joint purpose (Newman, 2011).

Consequently, complex systems do not allow simple reduction. Because of this, it is often difficult to understand the behavior of a complex system, and consequently it is not possible to create a simple, yet representative model (Rouse, 2007). This problem is especially relevant to managers, as they face complex problems in their environments daily. Furthermore, complex adaptive systems (CAS), defined by Miller and Page (2009) can be described by multiple key attributes that can be characterized by the factors affecting the systems’ behavior, such as: self-organizing, emergence, nonlinearity, and adaptability (Walden et al., 2015).

Eventually a new theory emerged as research was conducted into the complexity issue. The new theory, called “complexity” theory, is based on patterns, emergence and iterations. Complexity occurs when the dependencies between the elements within the system gain relevance (Arthur, 1999; Danilovic and Browning, 2007). All elements and their interactions have individual relevance, and removing any element from the system may lead to the collapse of the entire system’s behavior (Martin, 1996; Walden et al., 2015). The complexity theory has brought important insights for science, but little has been done trying to explore the policy aspects of this new approach (Allaire et al., 2012).

Furthermore, complexity in organizations escalates as the processes involve a growing amount of people and external organizations, expands to different regions, and faces evolving technologies. All these factors can increase the relevance and amount of interactions, resulting in more interlinked and complex systems (Luo and Wood, 2017). From this perspective, the universe is built of complex systems, all of which are constantly adapting to their surroundings, hence the “adaptive” in CAS. Moreover, CAS are also systems whose elements can be dynamic and self-organizing. Consequently, CAS are constantly changing (Miller and Page, 2009).

The mentioned interactions between systems’ components can generate the need of more elaborated levels of organization, and form the backbone of new structures, a phenomenon referred to as emergence (Boardman, 1990; Martin, 1996). The elements or agents of a complex organization can be organizational units, individuals, groups, etc. Furthermore, unofficial organizational groups have the ability to significantly twist the intended structure of the organization, a clear example of the complexity conditions.

In addition, elements behave in line with their individual goals and interests. Moreover, in real organizations they often behave in contradiction to the organizational goals. CAS have many properties, and the most relevant according to (Miller and Page, 2009) are:

a. Emergence: Instead of behaving as planned, elements in a system can behave in a seemingly random manner. From this uncontrolled behavior, new unexpected patterns and interactions may emerge within the system.
b. Self-organizing: CAS lack of a permanent hierarchy. The systems instead constantly adapt to their surroundings and shuffle their organization accordingly over time. The desirable case for this characteristic is that the reorganization within the system is motivated by learning and done on a best-fit evolution.

c. Organizational adaptation: The system and its elements can evolve accordingly to fit changing environments and conditions.

d. Nonlinearity: Not all elements within a CAS are equally relevant or have equally relevant interactions. Therefore, the overall behavior of the system does not change linearly in accordance with specific changes in some elements.

2.2 Decision-making process in complex organizations

In modern businesses and organizations, there is a large amount of factors that influence and have to be considered during the decision-making process (Fabac, 2010), thus creating a complex decision-making environment. At the same time, decision-making has different implications whether if it is done in the early design phase or in the late stages of a process (Mejía-Gutiérrez and Carvajal-Arango, 2017). Under the current accelerated environment of businesses and organizations, decision-making has emerged as an essential part of the organizational and managerial operations. Furthermore, throughout every company, the practice of systematic decision-making is strongly linked to success and innovation (Akdere, 2011).

Decision-making as a process can involve individuals, groups and even entire organizations, and it is often linked to problem solving, but it is also a vital element of strategic planning (Akdere, 2011) and strategic decisions (Tan and Shen, 2000). As pointed out by Chu and Spires (2000) the strategy’s quality can be gauged by evaluating choices or outcomes with a normative strategy as reference. However, the common ambiguity of problems generates a large amount of possible solutions, and it is not possible to understand fully the suitability of a solution before its implementation (Priem and Price, 1991). Decision-making becomes further complex due to the multitude of influencing factors, actors and activities involved (Danilovic and Browning, 2007). As a result, creative generation of solutions is perceived as vital to for success in most organizations (Rossiter and Lilien, 1994). Therefore, managers should be able to define problems, but also develop and implement solutions efficiently (McFadzean, 1999). Hence, training managers in decision-making tools and methods is now elementary (Fandt, 1993).

Furthermore, decision-making provides a sense of “ownership” to the members of an organization involved in a decision, thus reducing to an extent the perception of a top-down management and mitigating the employees’ resistance to change (Smith, 2001). Moreover, decision-making exercises are intended to encourage the people involved to
evaluate and review as critically as possible their assumptions (Schweiger et al., 1986). Simultaneously, the best available solution is more likely to be reached through considering the most comprehensive array of influencing factors (Rausch, 2007).

Decision-making can be performed in a wide array of ways, such as brainstorming, flow charting, democratic decision-making, etc. (Akdere, 2011). However, regardless of the importance of the decision-making processes in the organizations, a large gap in knowledge regarding the proper usage of decision-making in some organizational environments still exists (Akdere, 2011).

Decision-making is also perceived as an important leadership exercise (Saaty, 1985). Saaty (1985) proposed a structural modelling method for decision-making called analytic hierarchy process (AHP), which consists on a qualitative structure supported by numerical weights. AHP is intended to be used directly by practitioners though, in the case of highly complex problems, technical or computational assistance may be used (Saaty, 1985).

To be able to make the decisions there is a need to limit uncertainty. Different types of decision-making deal with different types of uncertainty (Eckert and Clarkson, 2010). There are also different types of decisions. Each of these types of decision deal with different uncertainty levels. Managers must focus on recognizing, understanding and mitigating organizational uncertainties. Moreover, most decision problems do not have good or universal support tools or methods. A systematic approach can be used to deal with complexity and uncertainty (Danilovic and Browning, 2007).

2.3 Systems engineering

Systems engineering (SE) is generally considered a holistic approach, containing several research methods. Research methods should recognize research questions and generate a resilient problem solving strategy, while providing validation of the results (Bahill and Gissing, 1998; Booth et al., 2003). SE is a very important part of activities like design & operation, training & support, cost & schedule, test, manufacturing, disposal, etc. (INCOSE, 2015; Sage, 1992). One commonly used definition of SE is “an interdisciplinary approach to enable the realization of entire successful systems” (Sage, 1992; INCOSE, 2015). Moreover, SE as a discipline focuses on “the design and application of the whole (system) as distinct from the parts” (Blanchard and Fabrycky, 2013).

SE targets to understand the customer needs and characterize the specific requirements of a complex system (Blanchard and Fabrycky, 2013). Furthermore, SE belongs to the basic group of disciplines that seek to generate solutions that meet the requirements of all stakeholders in a sustainable manner. The SE approach, according to Haskins (2006) and MITRE (2014), takes into the point of view the technical, economic and social aspects of a company as a complex system, facilitating the most satisfactory outputs. Moreover, SE enables the structuring of complex processes from design to operation (Sage and Lynch,
According to Eisner (2008), SE is a top-down focus iterative approach, targeting the fulfilment of the system’s requirements in a nearly optimal way. Bahill and Gissing (1998) proposed a functional method for system design at the lifecycle phase. Each function of the proposed approach (Bahill and Gissing, 1998) could be applied to every step of a process and can be used as research fields per se, such as functional analysis, requirements engineering, conceptual design, configuration management, architecture of a system, etc.

The purpose of the systems engineering handbook by the International Council on Systems Engineering (INCOSE) (Haskins, 2006; INCOSE, 2015), is to present the main process activities carried out by systems engineers through the life cycle of a system as a whole. In addition, SE also presents a broad array of basic system concepts that expand the thinking of the SE practitioners (Sage, 1992; Simon, 1962; Walden et al., 2015).

Engineering systems can exist at various scales of complexity. Engineering systems is a research field with the main focus on “large scale” complex system (Bartolomei et al., 2012). SE could be used in design phase and operation phase. Example of use of SE in operation of complex organizations include The US Department of Defense (DoD), The North Atlantic Treaty Organization (NATO), Organization of the Petroleum Exporting Countries (OPEC), United Nations (UN) etc. (Bartolomei et al., 2012). One common issue of the SE approach is that eco-design practices are often left out in the early design phases of complex systems. The SE approach demands for balance between the variant of SE needed by the situation, and the potential of SE in the organization (Beasley and O’Neil, 2016) to optimize these two factors. The application of SE should be perceived as the means to an end, rather than an outcome (Beasley and O’Neil, 2016). Based on case studies, the implementation of SE to different domains shows its flexibility.

According to the SE Vision 2025 (Beihoff et al., 2010; INCOSE, 2014), SE is still open for further expansion. The expansion can be to (1) further domains, such as adaptation to emerging industries, further development of SE tools to fully use the capabilities of new digital technologies, further involvement in cyber and virtual engineering. (2) Deeper involvement in education. (3) Of course, further expansion of the SE theory, and the methods and tools that may come with the SE theory’s expansion. The MITRE model (MITRE, 2014) of SE is constituted by the following five core sections: “Enterprise Perspectives”, “Systems Engineering Life Cycle”, “Systems Engineering Planning and Management”, “Systems Engineering Technical Specialties” and “Collaboration and Individual Characteristic”.

Kasser (2007) introduced the Hitchins-Kasser-Massie (HKM) as an approach for organizing activities and developing skills to carry out activities objectively. According to Maier (2009), the designer of a system architecture is not restricted to high level planning, but can also go deep into the specifics of subsystems within the high-level structure.
2.4 Methods of problem solving used in system engineering

This dissertation presents a decision-making oriented vision of operational decision-making and its support within the process industry, and comprises a largely interdisciplinary scope. The case study used is in the pulp and paper industry in Finland, and the presented results have been applied and validated within this context. The main purpose of the study is to guide the reader to awareness of the current practices about operative decision-making methods that are continuously being developed. The study introduces a developed methodology and its rationale to approach decision-making systematically.

Design and development of methods for complex problem solving in organizations is especially challenging to navigate and manage. For example, Knippen and Green (1997) described problem solving by “bringing a group of individuals together to analyze a situation, determine the real problem, look at every possible solution, evaluate each of the solutions, and choose the best one for their purposes”. Research has been conducted on numerous process models to understand, manage and improve design activities supporting decision-making for problem solving in process industry (Matasniemi, 2008). Therefore, research in SE is applied in general to real-world systems and companies. However, a single model cannot manage the complexity of all the issues, and because of this, multiple models are being developed with diverse targets of formulation identification and improvement.

In this dissertation, a conceptual framework that proposes models in relation to each other is presented; using existing methods for new problem solving concepts, taking into account different methods addressing different issues. The framework gives new application of the existing methods and is used to address how to structure and manage engineering design activities in complex organizations, within the context of the Finnish pulp and paper industry. Within this context, the framework systematizes the engineering design activities, involving a broad spectrum of stakeholders. The proposed approach is divided into two main stages: First part indicate how to structure engineering design activities and second part indicate how to manage them.

Therefore, the framework of analysis conceptualized in this dissertation intends to answer the following questions;

1. How to structure engineering design activities:
   - What to identify? – (activities) Publication I
   - Why to analyze? – (activities) Publication II and IV

2. How to manage engineering design activities:
   - Who organizes design activities? – (engineers and designers) Publication III
   - How to improve design activities? – (through a systems engineering approach) Publication V and VI
The SE approach is based on systems thinking (Cheekland, 1999). Systems thinking is done through “discovery, learning, diagnosis, and dialog that lead to sensing, modeling, and talking about the real world to better understand, define, and work with systems” (Boardman and Sauser, 2013). Systems thinking is a “unique perspective on reality, a perspective that sharpens our awareness of whole and how the parts within those wholes interrelate” (Boardman and Sauser, 2013; Duczynski, 2017).

While a system is acknowledged as the conjunction of its elements, thus systems thinking takes into account the prevalence of the system as a whole, as well as the prevalence of the relationships of the system’s elements to the system as a whole (Boardman and Sauser, 2013). Naturally, a problem in a system becomes increasingly complex with the level of uncertainty in its parameters and their configurations (Matasniemi, 2008). Simultaneously, the interactions between a system and external systems can accelerate or hinder the solution reaching process (Windahl and Lakemond, 2006).

According to Ericsson and Hastie (1994), several researchers of technical and nontechnical fields have used several methods to address system thinking and problem solving. Bahill and Gissing (1998), for example, studied the revaluation of systems engineering concepts through systems thinking, creating a seven-steps process known as SIMILAR that stands for: 1) “State the problem”, 2) “Investigate the alternatives”, 3) “Model the system”, 4) “Integrate”, 5) “Launch the system”, 6) “Assess the performance” and 7) “Revaluate”. Systems thinking helps understanding how systems interact within their context, the circular causation of their variables, which can both be the root and the consequence of an effect, and their non-linear behavior and how to manage these characteristics (Martin, 2007).

On the other hand, problem-solving theory grows from focus on the element, into identification of a problem, towards the search for a solution (Newell and Simon, 1972). Within systems engineering, the role of problem solving is well defined as the “investigation and resolution of complex problems arising from the conception, articulation and implementation of large-scale systems” (Matasniemi, 2008).

One of the most common problem solving models is the SARA model, “Scanning, Analysis, Response, and Assessment”, proposed by Spelman and Eck (1987) which concentrates on a linear approach. Another model, proposed by Knippen and Green (1997) is the seven-phase method for problem solving.
3 Research design

This chapter presents the research design of the dissertation. Research can be defined as an activity that contributes to understanding a phenomenon (Kuhn, 1996). Research design describes the selection of research methods suitable for the research problem. Starting with the research approach on which this research is based on, followed by the research methods used and methodological choices made. Last, a section elaborating on the quality of research closes the chapter.

3.1 Research approach

The research philosophy forms a basis for the research strategy, data collection methods and data analysis of the research. Philosophical aspects and questions exist behind every research method and methodological approach and thus define the ways it is possible to provide new knowledge through research (Eriksson and Kovalainen, 2008).

The three main philosophical standpoints in social sciences recognized by Guba and Lincoln (2005) are “social constructivism”, “positivism” and “post-positivism”. Positivism stands for the belief that we live in a deterministic universe, where the theories can be derived to explain everything that can be observed or measured (Eriksson and Kovalainen, 2008). Post-positivism, on the other hand, acknowledges inherent biases, thus emphasizing the need for data triangulation and validation (Eriksson and Kovalainen, 2008). Constructivism implies that researchers “build” a world-view based on their own individual observations, from which theory emerges derived from recognized patterns (Creswell, 2013; Eriksson and Kovalainen, 2008). Furthermore, social constructivism implies that reality is built from the collective and subjective observations of multiple individuals and their interactions, a philosophical tradition often advocated by social sciences scholars and used for qualitative research (Creswell, 2013; Guba and Lincoln, 2005). A positivist scientist aims to find generalizable theory, and in contrast, a post-positivist or constructivist will search for detailed and specific case descriptions.

Moreover, it is common to adopt different philosophical positions over time (Creswell, 2013; Järvensivu and Törmö, 2010). This is referred to as pragmatism, where the focus is given to the problems and questions, rather than to the methods, thus not committing to any particular method or specific philosophy, providing a degree of “freedom of choice” (Creswell, 2013). This research follows philosophically guidelines of constructivism and pragmatism.

Data collection can be done through qualitative, quantitative or both approaches as best fitting for the different types of data analysis (Onwuegbuzie et al., 2009). In this dissertation, qualitative (Publications I, II, III and VI) and quantitative (Publication IV and V) methods were used as found best fit for the specific analyses.

The deductive reasoning sets its foundation on theoretical knowledge, further expanding theory from the knowledge and validates the new theory through empirical experiments
(Kovács and Spens, 2005). On the other hand, *inductive* reasoning derives theoretical knowledge directly from empirical observations, with limited or no previous theoretical knowledge (Kovács and Spens, 2005). The third research style is *abduction*, which consists on applying theory from an existing conceptual framework to new phenomena (Dubois and Gadde, 2002). For the publications used for this dissertation, Publications I and IV use abduction logic, while Publications II, III, V and VI use inductive reasoning.

Furthermore, research results can be categorized in several ways. In this dissertation, the research results are categorized into *descriptive* and *exploratory* according to Yin (2008). Descriptive results describe the phenomenon under study by its qualitative characteristics and exploratory results focus on expanding the understanding about the phenomenon. The case studies performed in publications III, V and VI were descriptive exploratory single case, while in publication I, II and IV was descriptive exploratory multiple-case.

### 3.1.1 Design science

*Design Science* can be seen as the basis of problem-solving research (Holmström et al., 2009). Furthermore, design science research is comprised by a variety of fields, e.g. action science, action research, action innovation research, participatory action research, participatory case study, and academe-industry partnerships (Holmström et al., 2009).

Design science is a type of pragmatic research that focuses on the development of informative tools to solve real-world problems. Moreover, design science integrates the focus on information technology (IT) tools with prioritization in the application domain (Hevner and Chatterjee, 2010). Therefore, design science targets the development of novel techniques to tackle newfound complex problems, commonly faced in engineering sciences (Hevner et al., 2004).

Design science research consists of the application of existing knowledge to solve a problem and learn about it. The results of design science research are concrete solutions to the research problem, and at the same time, the academic framework is defined. An artefact, which solves a research problem, can be a model, a method, a framework, a process, a system, or a physical artefact (Peffers et al., 2008).

Peffers et al. (2008) presented the six common steps in design science research as following:

- **Step 1: Problem identification and motivation.** Define the research problem and justify the solution, thus requires knowledge to state the problem and recognize the importance of the solution.
- **Step 2: Define the objectives for a solution.** The objectives should be formulated from the problem, but also be reasonable and realistic.
• Step 3: Design and development. Create the artefact construct, model, method, or instantiations. The artefact should be viable and bridge the gap between the problem and the solution.

• Step 4: Demonstration. Demonstrate the use of the artefact to solve the problem. Verify that the artefact considers all relevant variables and produces the intended format of results.

• Step 5: Evaluation. Observe and measure how well the artefact solves the problem. Compare the objectives of the solution to actual observed results. At the end of this activity, researchers can decide to iterate back to step 3 if needed.

• Step 6: Communication. Draw conclusions and publish the results or apply the artefact as a permanent solution to the original problem.

Model building, as a branch of design science, is a method of problem solving used to face real world problems (van Aken, 2004). Analytical modelling uses deductive logic in describing constructs or processes (Demski, 2006). The main advantage in using models in research is transparency. Models have been used in management research, e.g. models can support decision-making process of managers in a company (Mun, 2008). However, design science can be hindered by lack of data access or insufficient data recording (Carson et al., 1995). In publication VI, design science is applied through a proposed model to support the decision-making process.

Analysis and Synthesis etymologically originate from Greek terms that stand for loosen up and tighten up respectively, and refer to research strategies (part of design science research) rather complementing each other (Ritchey, 1991). Analysis refers to the relevant data collection on the subject under study, while synthesis consists on establishing a cohesive whole, disregarding of no relevance. Both activities are performed in a loop, until the resulting data is tightly linked to the subject of study, or additional gathering of data no longer contributes to the analysis. According to Suri (1998), the synthesis process should be inductive, but also flexible rather than being limited to a specific procedure. Moreover, Suri (1998) explains that synthesis of qualitative data is done with the purpose of a more comprehensive understanding of a research subject.

The main driver of systems engineering is system design (Blanchard and Fabrycky, 2013). Systems design is comprised of 4 phases iterative phases (analysis, synthesis, design and evaluation) presented in a simplified manner in Figure 4. The process is integrative and iterative as shown in the figure. Continuous system design can be applied to any process or system, potentially providing innovative benefits (Blanchard and Fabrycky, 2013).
The analysis phase consists of measurement and forecasting of technical performance values for design dependent parameters (DDP). Simultaneously, design-independent parameters (DIP) should be considered and forecasted (Blanchard and Fabrycky, 2013). Analysis is linked to synthesis and evaluation through modelling and adaptation of the observed DDPs and DIPs (Blanchard and Fabrycky, 2013).

Synthesis refers to the creative process of compiling relevant known data into useful arrays, with the purpose of meeting customer requirements and objectives (Blanchard and Fabrycky, 2013). The synthesis process is carried out by design teams using computer-based tools.

Design refers to the activity of projecting and proposing a perceived set of customer requirements, often presented in the form of functions or activities. Design often reaches success by using both bottom-up and top-down approaches. The obtained functions and activities are integrated into subsystems, and the suitable options are then the subject of evaluation (Blanchard and Fabrycky, 2013).

Finally, evaluation consists on scrutinizing the solutions or options generated in the design phase. The scrutiny is done either against the customer requirements or other proposed solutions, while taking into account the DDPs and DIPs, where DDPs are usually internal factors and DIPs tend to be external factors (Blanchard and Fabrycky, 2013). Because ultimately the decision on the solution to be applied is subjective, several
Research design

of the best rated alternatives after evaluation should be presented to the customer to make the final choice (Blanchard and Fabrycky, 2013).

3.1.2 Systems engineering

As described in Section 1 and in Figure 2, many systems engineering methods and tools are used in design science approach applied in this thesis. The presentation and technical application map have been presented in the dissertation.

Morphological analysis (MA) was originally introduced by Zwicky (1969) as a non-quantified modelling method for identifying, structuring and studying complex problems (Ritchey, 2010). In addition, morphological analysis technique is a decomposition method that breaks down a system into subsystems with several attributes and selects the most valuable alternative (Yoon and Park, 2005). It enables problem representations using a number of dimensions, which are permitted to assume the number of conditions (Eriksson and Ritchey, 2002; Ritchey, 2006; Ritchey et al., 2002). MA requires a multidisciplinary group of 5–7 experienced experts (Yoon, 2008; Yoon and Park, 2007, 2005), representing different aspects of the issues involved. In this thesis, the use of morphological analysis allows the decision-making process of identification and selection of appropriate complex design activities to be structured and accelerated in a multidimensional matrix.

Sensitivity analysis (SA) is a technique that deals with the investigation of potential changes and errors in variables and assumptions, and their impacts on the results of underlying models (Mysiak, 2010). In normal mathematical modeling and simulation, SA is used to evaluate how the changes of the variables or assumptions affect the results (Ferretti et al., 2016; Mysiak, 2010). The use of sensitivity analysis was applied to optimize morphological analysis with the aim to find the most influential combinations of the cross consistency matrix to reduce the time iteration. In this thesis, the use of SA was to integrate with MA as a concept with high potential for time reduction (Buzuku and Kraslawski, 2019).

Design Structure Matrix (DSM) introduced by Steward (1981a, 1981b), is a compact, matrix representation of a project network, which aims to show all the dependencies and interactions between the system elements (Eppinger and Browning, 2012). DSM is a network-modelling tool to perform the analysis and the management of complex systems (Danilovic and Browning, 2007). DSM enables the deconstruction of the organizational and functional components of a system by eliciting the relationship between components in ways that make trade-off analyses more understandable and manageable (Browning, 2014; Danilovic and Browning, 2007; Rouse, 2007). In this thesis, MA is integrated with DSM to facilitate modelling procedures in problem solving of complex problems.

Boolean logic – it is a branch of algebra first described by George Boole in 1847. According to the Oxford Dictionary, Boolean denotes a “system of algebraic notation used to represent logical propositions by means of binary digits (1 or 0, true or false,
etc.) mostly used in computing and electronics”. In this thesis, Boolean logic provides an additional feature to DSM, by allowing to analyze multiple cases in parallel as a single system of equal parameters.

Multiple criteria decision-making (MCDM) can be generally described as the process of selecting one from a set of available alternatives, based on a set of criteria, which usually have a different significance (Saaty, 1985). MCDM and ranking methodology - allows the evaluation of different features of a system by a given value of importance (Saaty, 1985).

3.2 Methodological choices of the research

The literature on decision-making in industrial organizations is continuously growing, thus gaining complexity, and this dissertation tackles this field through exploratory research, qualitative research, single and multiple case studies. According to Eisenhardt and Graebner (2007), exploratory research targets the closing of literature gaps in literature by expanding the existing theory.

In this dissertation, a variety of methods and tools are used, and some further integrations or combinations are used. Data collection (and data itself) can be qualitative, quantitative or mixed in nature, where qualitative data is often represented by text or words and quantitative data is represented as numbers or values (Creswell, 2013; Eriksson and Kovalainen, 2008). In design science, often a combination of this data is applied (Creswell, 2013). Some characteristics of qualitative and quantitative research are presented in Table 2 adapted from (Eriksson and Kovalainen, 2008; Myers, 2013).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Qualitative research</th>
<th>Quantitative research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goals</td>
<td>Discover and understand observable phenomena</td>
<td>Accumulation of observations that confirm existing theory</td>
</tr>
<tr>
<td>Paradigm</td>
<td>Phenomenological</td>
<td>Positivist</td>
</tr>
<tr>
<td>Research style</td>
<td>Action research</td>
<td>Surveys</td>
</tr>
<tr>
<td>Research methods</td>
<td>Ethnography</td>
<td>Simulation</td>
</tr>
<tr>
<td>Methods (examples)</td>
<td>Case study research, interviews, content analysis</td>
<td>Laboratory experiments, multivariate statistical analysis</td>
</tr>
<tr>
<td>Point-of-view</td>
<td>Subjective</td>
<td>Objective</td>
</tr>
<tr>
<td>Sample size</td>
<td>Small</td>
<td>Large</td>
</tr>
</tbody>
</table>

Specifically from a systems engineering approach, qualitative research and (multiple or single) case study research are mainly used (Eisenhardt and Graebner, 2007b; Haskins, 2006; Yin, 2008). In this research, qualitative methods are more suitable due to the textual
nature of the data (Edmondson and McManus, 2007) related to complex decision-making in organizations. Furthermore, qualitative methods provide a holistic grasp of complex phenomena, particularly in complex decision-making in organizations (Creswell, 2013; Eisenhardt, 1989; Yin, 2008).

In accordance to the pragmatic research approach, this dissertation focuses on the problem and adapts suitable methods (Eisenhardt and Graebner, 2007b; Yin, 2014). Publications I, II and IV are analyzed through multiple case study, while single case study is used for Publications III, V and VI. Moreover, both creative and analytical methods are used in this dissertation, as these methods are known to be suitable for generating new theory in management and decision-making at the early design stage (Eisenhardt and Graebner, 2007b; Isom, 2001). A summary of the methodological choices is presented in Table 3.
### Table 3. Overview of the methodological choices in individual publications

<table>
<thead>
<tr>
<th>Publication I</th>
<th>Title</th>
<th>Research objective</th>
<th>Research approach</th>
<th>Research method</th>
<th>Data collection</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Use of design structure matrix for analysis of critical barriers in implementing eco-design initiatives in the pulp and paper industry&quot;</td>
<td>To recognize and assess the main barriers for implementing eco-design for sustainable manufacturing in the pulp and paper industry</td>
<td>Qualitative</td>
<td>Interview</td>
<td>9 semi-structured interviews at three major companies: B, C and D</td>
<td>Qualitative data analysis</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Publication II</th>
<th>Title</th>
<th>Research objective</th>
<th>Research approach</th>
<th>Research method</th>
<th>Data collection</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Overview of the interdependencies of barriers for implementing eco-design initiatives: DSM and Boolean visualization approach&quot;</td>
<td>To analyze, visualize and explore the potential of integrating eco-design for sustainable manufacturing in the pulp and paper industry</td>
<td>Qualitative</td>
<td>Multiple case study</td>
<td>9 interviews at three major companies: B, C and D</td>
<td>Qualitative data analysis</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Publication III</th>
<th>Title</th>
<th>Research objective</th>
<th>Research approach</th>
<th>Research method</th>
<th>Data collection</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Supplementing morphological analysis with a design structure matrix for policy formulation in a wastewater treatment plant&quot;</td>
<td>To investigate the potential of integrating design modeling methods supporting complex problem solving for environmental policy management</td>
<td>Qualitative</td>
<td>Case study</td>
<td>8 interviews; follow-up and one workshop in company A</td>
<td>Qualitative data analysis</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Publication IV</th>
<th>Title</th>
<th>Research objective</th>
<th>Research approach</th>
<th>Research method</th>
<th>Data collection</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Analysis and ranking of drivers for eco-design implementation in the Finnish pulp and paper industry&quot;</td>
<td>To identify and rank the key drivers from all major pulp and paper companies that speed up the improvement of eco-design implementation.</td>
<td>Qualitative</td>
<td>Interview</td>
<td>9 semi-structured interviews at four companies: B, C and D</td>
<td>Qualitative data analysis</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Publication V</th>
<th>Title</th>
<th>Research objective</th>
<th>Research approach</th>
<th>Research method</th>
<th>Data collection</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Optimized morphological analysis in decision making&quot;</td>
<td>To develop the CCA as a part of MA by exploring the potential time optimization for the application of CCA at the bottleneck of the iteration process.</td>
<td>Conceptual/Qualitative</td>
<td>Design science; Case study</td>
<td>1 focus group – 2 days' workshop in company A</td>
<td>Quantitative synthesis analysis</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Publication VI</th>
<th>Title</th>
<th>Research objective</th>
<th>Research approach</th>
<th>Research method</th>
<th>Data collection</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;A case study of complex policy design: The systems engineering approach&quot;</td>
<td>To develop a systematic approach for generating and improving policy alternatives in the design of complex policy design.</td>
<td>Qualitative</td>
<td>Case study</td>
<td>Multiple case study at three major companies: B, C and D</td>
<td>Quantitative synthesis analysis</td>
</tr>
</tbody>
</table>
3.3 Case study research

Case studies provide a broad and contextual scope of analysis of situations and events happening in real life, which can be a person, a group or an event (Yin, 2014), for example, organizational processes (Yin, 2014). Under a case study setting, the elements or actors cannot be manipulated as they behave independently according to the context, where the researcher can only collect and analyze the data (Eriksson and Kovalainen, 2008; Yin, 2014). Case studies are not limited to any domain or area, and can support both qualitative and quantitative data (Yin, 2014). Furthermore, case studies are particularly useful when the phenomena under investigation cannot be separated from its natural context (Halinen and Törnroos, 2005), or in situations where there is limited previous knowledge of the phenomena (Geertz, 1973). In addition, the case study approach serves to expand the understanding on how the context and external factors influence the phenomena (Eisenhardt and Graebner, 2007a; Yin, 2008).

According to Yin (2014), case studies can serve one of five purposes: explain, describe, illustrate, explore or meta-analysis. In addition, case studies can be categorized into three groups: “descriptive”, “exploratory” or “explanatory” (Yin, 2008). A descriptive case study targets the description of the characteristics of the studied phenomena. Exploratory case studies focus on expanding the understanding of the phenomena itself. Finally, an explanatory case study attempts to provide recommendations on how to react to the phenomena under study. The case studies performed in publications III, V and VI were exploratory single case, while in publication I, II and IV was exploratory multiple-case. Exploratory and descriptive research can be the implementation of empirical work.

Case studies can be used to analyze samples or populations of any size, small samples produce specific data that could support findings under rather limited contexts, while wider sampling is more useful to support generalized theories (Suri, 1998). Therefore, researchers should be careful not to draw generalized conclusions from limited data (Suri, 1998). Case studies have been previously applied to analyze the complex design activities in the decision-making process (Borghini et al., 2010; Järvensivu and Törnroos, 2010). It is due to the ability of the case study research to provide broad understanding of the context that it is now the “method of choice” for research in organizations (Easton, 2010). Single case studies provide a profound understanding of phenomena in a specific setting (Dyer et al., 1991), hence allowing the developing of theory from the interactions of a system in a particular context (Van Maanen, 1979).

Multiple case studies provide a unique context that allows to compare across cases, but also verifies the replicability of the method, while providing additional cross-case data that could lead to generalized theories and conclusions (Dyer et al., 1991; Eisenhardt and Graebner, 2007a). While single case studies often focus on cases that are either unusual or extreme cases, multiple cases studies aims for contrasting or comparable cases for theory extension (Eisenhardt and Graebner, 2007a; Yin, 2008). Both single and multiple case studies are almost equally used for research (Piekkari et al., 2010). In the specific
case of multiple case studies, the replicability across cases could provide validation and include the reliability (Miles and Huberman, 1994). In this dissertation, multiple case studies was used in Publications I, II and IV.

3.4 Empirical data collection, data analysis and research process

For Publications I, II, and IV the data on design activities in pulp and paper industry for implementing the eco-design practices was collected in the year 2017. For Publication III the data was gathered in 2014. The data gathered for Publication V is the same data used for Publications III and VI. The data on research design activities for building and construction of a wastewater treatment plant (WWTP) in Brazil is collected for Publication V and VI. The data consists on the conceptual and detailed design, as well as construction and operation of a WWTP carried out in 2014 and 2015, collected from relevant stakeholders of four companies. All four companies operate in the forestry and pulp and paper sector, and have their headquarters in Finland, though they carry out operations globally. A list of the sources for each publication is presented in Table 4 for single case study and Table 5 for multiple case study.

Table 4. Demographic details from the international company involved in the single case study

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Company A</td>
<td>Consultancy services for companies in forest industry (pulp &amp; paper)</td>
<td>ISO 9001, ISO 14001, EN 1090-1:2009 + A1:2011</td>
<td>III</td>
<td>8 (out of 10) interviews</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>V</td>
<td>conceptual</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VI</td>
<td>10 (out of 10) interviews</td>
</tr>
</tbody>
</table>

Table 5. Demographic details from the international companies involved in the multiple case study

<table>
<thead>
<tr>
<th>Source</th>
<th>Company type</th>
<th>Quality certifications</th>
<th>Publications</th>
<th>Interviews in 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company B</td>
<td>Packaging, biomaterials, wood &amp; paper</td>
<td>ISO 9001, ISO 14001, OHSAS 18001, PEFC™, FSC® Chain of Custody</td>
<td>I, II, IV</td>
<td>3 (out of 9) interviews</td>
</tr>
<tr>
<td>Company C</td>
<td>Producer of graphic papers and suppliers especially papers</td>
<td>ISO 9001, ISO 14001, EMAS, OHSAS 18001, ISO 50001, ES+ Chain of custody PEFC, FSC, EU Ecolabel</td>
<td>I, II, IV</td>
<td>3 (out of 9) interviews</td>
</tr>
<tr>
<td>Company D</td>
<td>Forest industry of wood products pulp, board, tissue and cooking paper</td>
<td>ISO 9001, ISO 14001, Chain of Custody PEFC ST 2002-2013, FSC</td>
<td>I, II, IV</td>
<td>3 (out of 9) interviews</td>
</tr>
</tbody>
</table>
The data used for Publications I, II and IV was obtained from nine semi-structured face-to-face interviews (from Table 5) with expert representatives from the sustainability division of the aforementioned companies. Face-to-face interviews produce data immediately and the spontaneous nature of the responses reflect reality more accurately (Opdenakker, 2006). The interviews were carried out in a semi-structured manner to keep a focused approach to the data collection. Figure 5 introduces the arrangements of the research process.

The interviews took place during the first quarter of 2017, either at the Lappeenranta University of Technology (LUT) campus or at the personal office of the interviewees at their locations. Before each interview, the interviewees were given a brief introduction on the topic, methods and rights. All interviewees participated on a voluntary basis and the respective consent was given for this specific use of the data. The length of the interviews was one hour, and the information was registered through detailed notes. No recordings took place due to confidentiality. The interviews were followed up by a written questionnaire. From the interviewees and questionnaires, a total of nine usable detailed responses were obtained.
For Publications III, V and VI the data collection was conducted during autumn 2014 and spring 2015. The data collection consisted of an initial round of face-to-face interviews (from Table 4), followed by a two-day guided workshop with ten participants at the LUT campus. Figure 6 introduces the timeline of the data collection rounds and the interpretation of the publications.

Timeline of data collection and publications

Figure 6. Timeline of data collection and publications

3.5 Quality of the research

There are several criteria that can be used to gauge the quality of any research of which the most commonly used are reliability, generalizability and validity (Eriksson and Kovalainen, 2008; Miles and Huberman, 1994; Patton, 2014). Nevertheless, these specific type of criteria tends to be more representative of “quantitative, positivist and realist approaches emphasizing objective, accurate and replicable data” (Yin, 2008).

On the other hand, better fit for qualitative research is the metric of “trustworthiness” (Lincoln and Guba, 1985). Trustworthiness is built by criteria such as “confirmability, credibility, dependability and transferability” (Eriksson and Kovalainen, 2008; Lincoln and Guba, 1985). Because of the overall qualitative nature of the empirical research, the subjectivity of the researcher, these criteria are also used in the evaluation of these results.

Credibility refers to the “confidence in the truth” of the findings. It is associated to the perception of the researcher and subjects of research on how the reality is reflected in the empirical data (Eriksson and Kovalainen, 2008). Credibility of the research, thus, refers to the researcher’s familiarity with the topic and the sufficiency of the research data to merit the claims (Eriksson and Kovalainen, 2008). The sufficiency of the research material, in this case, is reflected by the data obtained through 19 interviews from all major pulp & paper companies operating in Finland. The author conducted all interviews
Research design

personally. However, the author also planned the research questions for all publications in cooperation with the co-authors who were involved in the research work. The authors chose the theoretical framework and fitted the empirical observation with them.

Transferability is associated to the “representativeness” of a sample. In other words, to what extent can research findings on a small sample be generalized or extrapolated to larger groups (Eriksson and Kovalainen, 2008). For example, the case studies used in this dissertation focused on a specific industrial sector within a defined geographical area. The transferability of the findings to other industrial sectors or other geographical areas is open for further research and debate. Transferability considers whether some kind of similarity can be found in other research contexts (Eriksson and Kovalainen, 2008). The chosen research strategy, case study research, sets limitations to the transferability of the results. As the cases are always bounded, they naturally have some specific traits, which cannot be generalized. Eco-design as an integral part of sustainable development has broad scope within the industrial field, in this case the focus was only the pulp and paper industry in Finland. Furthermore, as the study leans on an extensive theoretical background and combines the methods with empirical evidence, the framework constructed in the study can be validated, if applicable, in other industrial fields as well.

Dependability is associated to the degree of detail to which the qualitative data used for research is provided, allowing replicability (Eriksson and Kovalainen, 2008). Detailed qualitative data can be too extensive to be appended to a research report, or flat out incompatible (for example audio recordings to a printed publication). However, as the research becomes increasingly digitalized, the options to further share source data becomes increasingly available. In the case of this dissertation, when the used data was not made available due to data protection agreements, detailed descriptions of the data collection process was provided. Dependability also refers to the researcher’s responsibility for offering information on the fact that the process of the research has been logical, traceable and documented (Eriksson and Kovalainen, 2008). The interviews were written down through detailed notes of answers. Additional feedback was taken from each interview and the workshop. The central results were first gathered in figures, graphs and tables with different categories, by which the research data was then logically interpreted. All these documents used in the process were crosschecked by the co-authors and the supervisors and saved for later purposes.

Confirmability refers to the degree on which findings, data and conclusions are interconnected, but also understood similarly by others (Eriksson and Kovalainen, 2008). The researcher drawing the conclusions from the data is expected to provide the logical pathway from the data, through the methods and towards the conclusions. The findings can then be compared previous work for validation when possible. Solid confirmability, thus, proves that the data and interpretations made from it are not just the product of imagination. Several analysis frameworks were used in order to form a profound description of the study findings. The systematic approach of the analysis and synthesis was presented to simplify to the readers the links between the theoretical discussion, the
research data, and interpretations made from them. However, the conclusions were made within the research scope in the selected companies in one industry field.
4 Publications and review of the results

The chapter 4 presents the main objectives, research questions, findings and contributions of each publication of this dissertation. An overview of the objectives, methods and findings is given in the end of this section in Table 6.


Main objective

The main goal of Publication I is to recognize and assess the main barriers for the implementation of eco-design initiatives in the Finnish pulp and paper industry through the use of design structure matrix.

Methodology and empirical data

Design structure matrix (DSM) is a qualitative, uncomplicated and flexible modeling method utilized for structuring and managing complex design activities. For Publication I, DSM is used to scrutinize the barriers to eco-design deployment in the pulp and paper industry in Finland, analyzing data obtained from nine interviews conducted with managers and experts from the three major pulp and paper companies in Finland.

Main findings

By applying DSM method to the data obtained, it is possible to detect and assess the interconnections and relationships among the analyzed barriers for eco-design implementation. The findings assist to generate advice to policy makers for the management of eco-design implementation. The results indicate that the barriers “Lack of top management encouragement for training initiatives on eco-design process” and “Lack of employee involvement in eco-design initiatives” from management category show the most perceived interconnection from the Finnish pulp and paper industry’s scope. Moreover, the output of this publication indicates that the lack of collaboration between the company’s management and the governmental institutions constitute the most relevant obstacle to the implementation of eco-design initiatives.

Contribution

The principal contribution of this publication is to show that DSM method can be used to analyze barriers for eco-design implementation, particularly in the case study of the Finnish pulp and paper industry. The identified barriers to the implementation of eco-design in the pulp and paper industry in Finland are also categorized into four groups. The proposed DSM analysis emphasizes the barriers’ relationships within the management, institution, technology and stakeholders. Through clustering and
Publications and review of the results

visualization, DSM uncovers interrelations between barriers that were previously undetected. The findings expand the current literature on sustainable manufacturing by extending the understanding on the eco-design implementation process, and presents a group of policy recommendations to practitioners and decision-makers.

4.2 Publication II: Overview of the interdependencies of barriers for implementing eco-design initiatives: DSM and Boolean visualization approach

Main objective

The principal goal of Publication II is to analyze, visualize and explore the potential interaction of multiple cases in parallel and the interdependencies among their identified barriers of eco-design initiatives in order to study the industry as a unit by integrating Boolean logic to the DSM method.

Methodology and empirical data

A network modeling DSM approach is extended with 3-bit Boolean logic and is used to model, analyze and capture the barriers for eco-design process implementation in multiple cases simultaneously, involving interviews with nine managers in three major pulp and paper companies in Finland.

Main findings

The results show that the comparative analysis between different barriers under each category as well as barriers’ relationships, suggest implications for managing the eco-design implementation issues beyond the single company scope and at an industry level. The results reveal that barriers 1) “lack of employee involvement in eco-design initiatives” and 2) “lack of top management encouragement for training initiatives on eco-design process” are tightly interdependent for all studied companies. Thus, the results suggest the existence of an external common root for the barrier, and potentially the need for higher involvement of bodies external to the company, such as society, worker unions, governments, etc.

Contribution

The main contribution of this paper consists in presenting a multi-scenarios modelling approach applied to the Finnish pulp and paper industry that helps to explore, analyze and visualize the overall industry barriers’ dependencies in a single DSM. While DSM as a method is able to process multiple cases in a domain mapping matrix (DMM) and a multi-domain matrix (MDM), the traditional DSM method is able to analyze cases only in series. With the proposed approach, despite different companies having their independent barriers’ profile, the key contribution lies in enabling the DSM method to combine cases in parallel through Boolean logic, allowing to detect and analyze the common barriers
Publications and review of the results

that affect the overall pulp and paper industry in Finland. The findings contribute into the current literature on sustainable manufacturing by facilitating the decision-making to lawmakers, managers and stakeholders for finding the most relevant obstacles hampering eco-design implementation.

4.3 Publication III: Supplementing Morphological Analysis with a Design Structure Matrix for Policy Formulation in a Wastewater Treatment Plant

Main objective

The main objective of Publication III is to analyze and exploit the benefits of MA as a creative method and DSM as analytical method that are integrated into a framework and to show their potential for modeling complex systems.

Methodology and empirical data

A creative modeling method MA and an engineering design method DSM are proposed involving data from interviews with eight experts in a case of an international engineering and consulting company with headquarters in Finland operating at a local and international level.

Main findings

The findings show that both MA a creative method and DSM an analytical method methods work based on the principle of breaking down a system into subsystems as called “divide” and “conquer” technique. The findings highlighted that both of the qualitative methods heavily depend on expert’s judgments. By analyzing and modeling the process flow of the elements (policy measures) in DSM, it revealed that “Environmental Law Requirements” is the main policy measure that needs to be considered. The results show that the cluster of policy values “Environmental Law Requirements”, “Temperature = 40°C, settleable solid = 1ml/l”, “Cooling Towers”, “Training for safety measures in the working place” and “Water River Authority”, generated from MA, show the highest priority among the policy measures in DSM.

Contribution

Identification of the drawbacks of both methods highlights the advantages of their integration. The specific contribution of this publication is the identification of the avenues for MA and DSM integration. The integration of MA and DSM comes through, overall, as an interesting and useful combination of complimentary tools. In one hand, MA is a flexible tool that can be used for any purpose and in combination with any scientific method or approach. In another hand, some of the problems tackled using DSM are very well known entities, particularly how to synthesize and cluster solution space that are slightly compressed. Therefore, DSM seems to provide a promising way ahead.
4.4 Publication IV: Analysis and Ranking of Drivers for Eco-Design Implementation in Finnish Pulp and Paper Industry

Main objective

The principal objective of Publication IV is to highlight and rank the main drivers from all major pulp and paper companies in Finland, by investigating and measuring their impact. The drivers can then be assessed to improve the efficiency of eco-design implementation practices, and ranked as perceived from the perspective of industry’s experts using ranking methodology.

Methodology and empirical data

A multi-criteria decision-making (MCDM) ranking methodology is applied to data obtained from feedback from a group of nine experts and specialists. An assumption is made on the impact, or weight, of different factors evaluated from drivers for eco-design implementation, and a range of scenarios is applied to the weight factors measuring the drivers.

Main findings

The findings propose that drivers “Management’s idea”, “Customer demands”, from the group of drivers for implementation, and driver “Customer demands” from the group of drivers for continuation, hold the highest importance rank in all scenarios, therefore highlighted as the most influential drivers for eco-design implementation in the case study. In contrast, driver “One or few employees pushed idea” for implementation and drivers “Personal quest for a better environment” and “Increased employee satisfaction through environmental initiatives” for continuation showed the lowest perceived impact on eco-design implementation for all scenarios.

Contribution

The main contribution of this publication is the evaluation of the drivers for eco-design implementation for multiple pulp and paper companies in Finland, from an industry’s perspective. By providing understanding on the perception of the impact of different drivers for eco-design implementation, regulations and policies can be developed with the purpose of exploiting the inertia provided by the high-impact drivers. The findings contribute into the current literature and provide insights to practitioners and decision-makers in terms of managing eco-design implementation issues in the context of pulp and paper industry in Finland.
4.5 Publication V: Optimized Morphological Analysis in Decision-Making

Main objective

The primary objective of Publication V is to develop further cross-consistency assessment (CCA), as part of morphological analysis (MA), by exploring the potential time optimization for the application of CCA at the bottleneck of the iteration process. The paper presents a new approach to CCA matrix and sensitivity analysis (SA) using relative weights, which should find general applicability in MA.

Methodology and empirical data

MA is extended with sensitivity analysis and tested by a one-thousand iterations loop to estimate the potential optimization of the combination of the methods. The study focuses on conceptual theory. Furthermore, a case study analysis is conducted involving a wastewater treatment plant (WWTP) in a pulp and paper mill in Brazil.

Main findings

From the analysis of the results, a new way to optimize cross-consistency assessment (CCA) is presented. CCA relies on its iterative nature to reach to a solution space of a desirable size. Therefore, it is possible to optimize the usage of CCA by reducing the size of the iteration sample through sensitivity analysis (SA). By identifying the influence ratio of the cells (or value combinations) of the CCA matrix into the solution space, it is possible to single-out a reduced iteration group. Over a one thousand loop of randomly generated values in a middle-sized CCA matrix (and assuming an evenly distributed evaluation time per combination), an average of 63% of time reduction was obtained. Furthermore, the solution space was also reduced by 74% in average by using the SA method per iteration.

Contribution

These results show that targeted evaluation of a cross-consistency assessment matrix, supported by sensitivity analysis, has the potential to greatly reduce the evaluation time at every iteration. The method, though showcased within the boundaries of a case study, can be, in principle, applied to matrixes of any dimensions and to any range of values. The mathematical procedure to combine the methods was developed and presented in detail. The proposed approach of integrating MA and SA as a concept with high potential for time reduction be effectively used for managing industrial complexity. The major contribution of the research is to facilitate decision-making process in industry. More specifically, the optimization of CCA based model helps to facilitate decision-makers and managers to determine the relative importance of the combination sets in the CCA.
4.6 Publication VI: A Case Study of Complex Policy Design: The Systems Engineering Approach

Main objective

The primary objective of Publication VI is to develop a systematic approach for generating, designing and enhancing policy alternatives using a computational method that combines the diverse modelling methods of morphological analysis (MA), sensitivity analysis (SA) and design structure matrix (DSM).

Methodology and empirical data

A framework integrating multiple methods; MA, DSM and SA is developed. The approach is tested through a case study with data obtained from interviews with ten managers and experts from one Finnish pulp and paper company.

Main findings

A framework is proposed to address complex systems and it is divided into two stages: First stage is to generate and formulate policy measures or alternatives using MA, which in turn is optimized through SA, significantly reducing the iteration time. Second stage is to evaluate and improve the policy measures or alternatives with DSM to optimize the sequence of deployment and group in clusters. The main findings of the work are: 1) the integration of DSM with MA improves the overall process from conception and design to integration for improvement and management of complex systems. 2) The combination of DSM with MA significantly reduces the time in the decision-making process of policy design. 3) MA is optimized using sensitivity analysis, reducing the iteration step time by up to 80%. 4) Combining MA, SA and DSM methods can define absolute priority in decision support system (DSS). The findings highlight the capacity of combining MA and DSM to generate and improve the process of development of policy measures, enhance the design activities and overall improve the whole system’s structure for sustainable management.

Contribution

Part of the contribution of the work is that no work has been done before, or found in the strategy literature, on combining MA, SA and DSM for supporting decision-making in engineering design. This study makes two main contributions to theory and practice in the field of conceptual design. First, regarding literature on decision-making models, the proposed framework compiles and integrates existing modeling methods in a consistent and innovative way. Second, from the methodological perspective, this work extends to the application of policy formulation area by applying systematic modeling methods to policy design modeling in a pulp and paper wastewater treatment application. Overall, the proposed approach allows better understanding of the relationships among research design activities and categories, which seems essential to integrate sustainability in the
Publications and review of the results

conceptual phase. The findings contribute to the field of conceptual modeling by offering a systematic approach to integrate sustainability into policy design.

4.7 Summary of the publications

The goal of this dissertation was achieved through pursuing the following six specific objectives, each of which is dealt with individual publications.

1) To determine and assess the critical barriers for implementing eco-design in the pulp and paper industry. (Publication I)
2) To analyze, visualize and explore the potential interaction of multiple cases in parallel and the interdependencies among the identified barriers of eco-design initiatives in order to study the industry as a unit. (Publication II)
3) To analyze and exploit the benefits of MA as a creative method and DSM as an analytical method integrated into a framework, showing their potential use for modeling and managing complex systems. (Publication III)
4) To identify and rank the key drivers from all major pulp and paper companies in Finland, by investigating and measuring their impact. (Publication IV)
5) To develop further cross-consistency assessment (CCA), as part of morphological analysis (MA), by exploring the potential time optimization for the application of CCA at the bottleneck of the iteration process. (Publication V)
6) To develop a systematic approach for generating, designing and enhancing policy alternatives using a framework that integrates the modelling techniques of morphological analysis (MA), sensitivity analysis (SA) and design structure matrix (DSM). (Publication VI)

Publication III was the initial step of the research proposed in this dissertation. From this point, the author was encouraged to pursue further systematic investigation of the integrating avenues of diverse modeling techniques, as well as further development of the integrative framework for promoting sustainable management in industry. Consequently, the results of this publication set the research path that resulted in Publication V. In Publication V, MA receives an overhaul through the combination with SA, resulting in the time optimization applied afterwards in Publication VI. Publications I, II and IV are fully dedicated to the multiple case study of eco-design practices in the pulp and paper industry in Finland. Using a variety of methods (DSM, Boolean and Ranking methodology), the industry is analyzed from a perspective of barriers and drivers for eco-design implementation.

Finally, Publication VI thus stands as the fusion of the methodologies derived from Publications I, III and V, combined into a systematic approach framework to tackle complex systems. The proposed systematic approach is comprised of two stages;
1. First stage enables to formulate the problem, generate alternatives, select a course of actions, and evaluate continuously using MA, while using SA to optimize the iteration process of CCA.

2. Second stage allows analyzing, visualizing and improving alternatives using DSM.

Applying a solo case study approach allows relevant findings to surface in respect to the development of systems engineering approach and implementation. As a result, the paper VI addresses methods and approaches for the design, generation and evaluation of complex decision-making processes. Specifically, it discussed the use of General Morphological Analysis (GMA) and Design Structure Matrix (DSM) related to the establishment of a wastewater treatment plant at a pulp and paper industry in Brazil. Main findings are that the combination of GMA and DSM provide powerful tools to decision-makers and analysts to generate policy alternatives, reorganize alternatives into policy clusters, and prioritize between alternative policies. The paper also presents a method to rationalize sensitivity analysis of GMA output by applying relative weights to value (element) pairs in the cross consistency matrix. Overall, a practicable start-to-end approach for complex decision-making is presented. Taken together, the paper offers a consistent analytic approach encompassing generation and analysis of alternatives, and a framework for prioritization and decision-making in complex settings. The proposed systematic approach is shown in Figure 7.
Figure 7. Proposed systematic approach
Table 6. Overview of the individual publications and their main findings.

<table>
<thead>
<tr>
<th>Publication I</th>
<th>Publication II</th>
<th>Publication III</th>
<th>Publication IV</th>
<th>Publication V</th>
<th>Publication VI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Title</strong></td>
<td>“Use of design structure matrix for analysis of critical barriers in implementing eco-design initiatives in the pulp and paper industry”</td>
<td>“Overview of the interdependencies of barriers for implementing eco-design initiatives: DSM and Boolean visualization approach”</td>
<td>“Supplementing morphological analysis with a design structure matrix for policy formulation in a wastewater treatment plant”</td>
<td>“Analysis and ranking of drivers for eco-design implementation in the Finnish pulp and paper industry”</td>
<td>“Optimized morphological analysis in decision-making”</td>
</tr>
<tr>
<td><strong>Objective</strong></td>
<td>To identify and explore the critical barriers related to implementation of eco-design in pulp and paper industry and to use DSM to tackle the identified issues.</td>
<td>To identify, analyze, improve the visualization and explore the interaction of multiple cases in parallel and the inter-dependencies among their identified barriers related to eco-design initiatives.</td>
<td>To explore the potential for integration of MA with DSM for modeling complex systems in the environmental policy design context.</td>
<td>To identify and evaluate the key drivers from four major Finnish pulp and paper companies by using MCDM-Ranking methodology.</td>
<td>To develop MA by exploring the potential time optimization for the application of SA at the bottleneck of the CCA iteration process.</td>
</tr>
<tr>
<td><strong>Main findings</strong></td>
<td>The study address the barriers related to environmental strategies and provide the set of policy recommendations to managers and policy makers for managing eco-design implementation.</td>
<td>DSM tool combined with Boolean logic is used successfully to detect and analyze the common barriers that affect the Finnish pulp and paper industry. One barrier correlation (B7 with B8) is present for all studied cases.</td>
<td>The proposed two-phase integrated framework allows designers to tackle complex problems for design and modeling of environmental policy management.</td>
<td>The drivers with the highest and lowest rank are identified for all companies and all scenarios.</td>
<td>Optimization of MA through SA in a case study was achieved by time reduction of the iteration process by a factor close to 80%.</td>
</tr>
<tr>
<td><strong>Main contribution</strong></td>
<td>Identification of DSM as a viable method for addressing decision-making eco-design implementation in the pulp and paper industry.</td>
<td>A new feature is added to DSM by combining it with Boolean logic, allowing the comparative analysis in parallel of multiple design activities.</td>
<td>Identify the drawbacks of MA, highlight the advantages of DSM, while showing the avenues for integration of both methods.</td>
<td>This the first use of MCDM-Ranking for analyzing eco-design implementation analyzing multiple cases in the Finnish pulp and paper industry context.</td>
<td>SA is proven a successful tool to optimize the CCA matrix iteration process. A new methodology is presented to adapt the SA tool to any CCA matrix.</td>
</tr>
</tbody>
</table>
5 Conclusions

The purpose of this dissertation was to enhance the decision-making in complex organizations through applying a systems engineering approach.

The main objective was to enhance problem understanding and structuring and to advance decision-making for modeling and managing design activities in complex organizations. This was achieved by narrowing the gap identified in the complex systems literature on decision-making. In order to achieve this goal, the following two research objectives were set:

1. To identify and analyze key challenges and obstacles hampering engineering design activities and strategies in complex organizations.
2. To develop and implement a methodology for modeling and managing engineering design activities that advance the decision-making process in complex organizations.

The research topic was empirically based, primarily applying a qualitative research approach to a case study pulp and paper industry in Finland. This study builds over former research and literature sources, aiming to add contribution primarily to the decision-making process and systems engineering literature. The author proposes a framework for development of a methodology and tools to enhance the decision-making process in complex organizations. The framework is established on a systems engineering approach, based on existing methods and reformulated from the principles of systems engineering. This approach considers several methods from various research fields, and includes a creative method (MA), an analytic engineering method (DSM), mathematical methods (Boolean logic and sensitivity analysis) and decision methods (MCDM-ranking methodology). The proposed method is referred to also as a framework to highlight its capacity to supply a structure to analyze design activities.

Overall, this dissertation examined the phenomenon of complex decision-making methods in process of the Finnish pulp and paper industry. Its rationale, which could be relevant to any company or industry, was validated only in Finnish pulp and paper industry. The first chapter focused on describing motivation, positioning and the scope of the research, identified the research gap and formulated the research questions, setting the main aim and defining the specific objectives. The second chapter described the concept of organizations as complex systems, and some of the problem-solving methods used to enhance decision-making in complex systems, while mitigating complexity. The third chapter presented the general research design. Chapter 4 follows with a summary of the main findings from the six single publications. Chapter 5 discusses the relevant contributions of the dissertation. Therefore, in this chapter, the results are reviewed in respect to the main objectives and each of the three research questions. The theoretical and managerial implications follow, ending with limitations of the study and suggestions for future research.
Objective 1 was met by the identification of the gaps or disadvantages related to the used methods in their applications. In the case of this dissertation, those gaps are:

- The inability of MA to evaluate dependences and interdependences
- The inability of DSM to deal with parallel analysis of elements or multiple choices
- The inefficient iteration process of MA with CCA
- The lack of capability of DSM to analyze multiple cases in parallel
- The lack of literature on prioritization of barriers and drivers for engineering eco-design in the Finnish pulp and paper industry

In order to fill those gaps and to meet Objective 2, the methods used in this dissertation were combined and further enhanced, resulting in creative solution frameworks presented in Publications I through VI. In order to improve decision-making in complex organizations, three research questions were created. In general, these questions are addressed in the publications thus integrating the related elements into a systematic approach.

**RQ1. Can MA, DSM and MCDM-Ranking be used in decision-making for eco-design implementation in pulp and paper industry? (Publication I, II, III, IV, V, VI)**

The well-established SE methods addressed in RQ1 are brought to new applications. The possibility of using DSM, MA, and MCDM-Ranking for enhancing decision-making in the field of eco-design in the pulp and paper industry in Finland is explored for the first time in the literature. The methods are then further integrated and combined with other methods, or even with each other, to tackle decision-making regarding sustainable policy design to the implementation of a wastewater treatment plant, as well as analyzing the barriers and drivers for eco-design implementation. The studies were conducted through case studies involving experts and relevant stakeholders related to the pulp and paper industry. While combination of MA and DSM with other methods has been performed previously (Danilovic and Browning, 2007; Geum and Park, 2016; Im and Cho, 2013; Lee et al., 2009; Ritchey and de Waal, 2007; Sholeh et al., 2018; Wang et al., 2017), for the first time MA and DSM are integrated within the scope of this dissertation. The results show that DSM, MA and MCDM-Ranking are well-suited methods for enhancing decision-making within the engineering eco-design implementation in the pulp and paper industry scope. This is reflected in the contributions and results of Publications I through VI.

**RQ2. Can DSM method be further enhanced to improve the decision-making process in different sectors for eco-design implementation in pulp and paper industry? (Publication II, III, VI)**

After establishing DSM as a suitable method for analysis and improvement of decision-making for one case in the Finnish pulp and paper industry in Publication I, the task evolved to the enhancement of the method for improved performance of analysis in the
industry with the same scope. In order to address RQ2, DSM as a method was integrated for enhancement first with Boolean logic in Publication II, then with MA in Publication III, and finally within the framework of MA and SA in Publication VI. The integration of these methods and the improvements and enhancements presented in these publications are done for the first time in literature. By integrating Boolean logic to DSM, a new feature is added to the method that allows to examine several equivalent subjects in parallel and simultaneously, something that has not been done before. Moreover, by integrating DSM with MA and subsequently with SA, a framework for decision-making is created that helps to complement the weaknesses of the individual methods into a resilient decision-making method. As a result, Publications II, III and VI confirm that DSM can be further enhanced to improve decision-making for eco-design implementation in the pulp and paper industry.

RQ3. Can MA method be further enhanced to improve decision-making in pulp and paper industry? (Publication III, V, VI)

Similar as in RQ2, MA is first introduced as a suitable method for enhancement of decision-making sustainable policy design in Publication III. Thereafter, the task of finding a way to enhance MA usage, within the context of decision-making in the Finnish pulp and paper industry, was addressed. CCA, as part of MA, was found to have a bottleneck in its iterative nature, and thus optimization of this step became the target of improvement. In Publication V, CCA as part of MA is screened through sensitivity analysis in order to highlight the most influential elements in the matrix, in order to save time invested in elements of low or zero impact. As a result, the iteration time of a CCA evaluation is greatly reduced. The aforementioned optimization of CCA by combining it with sensitivity analysis has never been done before in the literature. Furthermore, MA is complemented as the initial step of a framework that uses also sensitivity analysis and DSM to generate resilient decision-making method validated within the scope of the pulp and paper industry in Publication VI. Therefore, in Publications V and VI it is shown that MA can be further enhanced to improve decision-making in the pulp and paper industry. This study is the first attempt to develop an approach extending MA with SA and then MA with DSM. The proposed framework can potentially serve as the foundation for a model application for any industry or company, but here it was validated only in the Finnish pulp and paper industry.

5.1 Theoretical contributions of the study

This study makes theoretical contributions within the field of decision-making in complex organization by addressing the study objectives and providing managerial implications. First, some of the methods used throughout the thesis and the publications have never before been used in the literature. Specifically, the application of MA and DSM as tools to manage the implementation of eco-design in the Finnish pulp and paper industry is completely new to the literature.
Within the Finnish pulp and paper context, the methods originally applied were further improved or expanded. Morphological analysis, and cross-consistency assessment within MA, is a well-established method of analysis. Despite of this, it was possible to further optimize this method by significantly reducing the iteration requirements using sensitivity analysis for identifying the most impactful variants. Optimization of MA and CCA with sensitivity analysis has also never been done by anyone else.

Furthermore, DSM has been further expanded by combining it with Boolean logic for parallel multiple case analysis. DSM as a method is capable of highlighting and understanding the interrelations of the variables within a system. By combining DSM with Boolean logic, an additional feature was added to DSM, which was before unable to analyze more than one case at a time. DSM combined with Boolean logic allows the user to analyze different cases and broaden the scope of analysis, in the test case providing an overview of an industry rather than a single company. This new feature and this novel use of Boolean logic with DSM was applied for the first time in literature.

Overall, the methodological contribution of this dissertation also consists in the formulation of an integrated framework for structuring and managing complex design activities in organizations. By combining of a top-down and bottom-up technical approaches, the improvement of decision-making process from the industrial perspective was the target.

Another contribution point of this dissertation is in the field of problem solving and decision-making, by proposing a systematic approach for handling complex engineering design activities, supporting and improving decision-making in technical organizations.

Overall, the six Publications comprising this research provide contributions to the theoretical understanding of how to facilitate decision-making process for structuring and managing complex design activities and decision-making in the pulp and paper industry in Finland.

This dissertation makes a case for advancing a theory of decision-making in complex organization as a development of a model by providing evidence and arguments supporting the findings. The study presents a model to support decision-making process by shedding light on the use of systems model to cope with the integration of sustainable concerns into strategic problems, where traditional multi-objective approaches are not sufficient due to the multi-dimensional and often non-quantifiable characteristics of the problems under analysis.

Moreover, the proposed approach adds theoretical contribution to the systems engineering literature by providing a systematic mechanism to problem solving and decision-making in complex technical organizations. Furthermore, through the implementation of the proposed framework in an industrial context, a case study showcased the applicability and utility of the approach in the context of SE.
5.2 Managerial implications

In this dissertation, complexity in organization systems is highlighted as the dynamic behavior of elements and the relationships between them. Decision-makers and managers have to address the uncertainty in the decision-making process, which may affect products and processes alike. Uncertainty surges from potential errors in assumptions about dependencies and the dependence on information exchange between domains and individuals that need to make decisions and solve problems, in complex technical organizations. Managing all of these aspects, methods and tools e.g. in engineering eco-design issues and other engineering problems in complex organizations requires approaches and expertise of several participants from diverse backgrounds.

In general, as indicated in the title of this dissertation, this thesis aims to supply relevant insights for industries, which want to peruse the facilitation of the decision-making process in complex organizations by applying a systematic approach. Arguably, different industries or companies are exposed to different costs, challenges and benefits from the proposed systematic approach, thus the implementation of the model could generate different results in different complex organizations.

Managerial implications incorporate the proposition of a novel approach to assist the decision-making process of projects and industry experts and managers of the Finnish pulp and paper companies. The implementation of the proposed framework allows designers and managers to become aware of the complexity of design measures or activities and to enhance decision-making and implementation of a decision support system. Therefore, providing managers a framework for prioritization of important design activities and formulation of environmental strategies to coordinate their effort in an effective way.

Specifically, Publication VI shows three managerial implications and the benefits of the proposed approach. First, the suggested approach allows decision-makers and managers to divide a complex problem into sub-problems to mitigate its complexity. This is done by using creative and analytical modeling methods and decision support tools. Second, the systematic approach proposed in this dissertation is practical, and can be employed in reality, potentially providing meaningful insights and enhancing decision-making in complex technical organization. Finally, since this study develops an integrative systematic approach for facilitating decision-making in the process industry, it can be used as the foundation for the future decision support method in practical decision-making. Another implication is expanding the understanding of what comprises a decision-making process, filling the gap between analysts, experts, decision-makers, managers and other stakeholders, or between research institutions and companies.

5.3 Limitations and suggestions for future research

The main limitation of this study, as it commonly happens in research, is data access. On one hand, engineering design activities supporting decision-making in complex
organizations is directly linked to engineering eco-design practices. However, not all pulp and paper companies in this case study share the same barriers, or have the same perception towards the barriers. Therefore, the companies’ reluctance to share data in a sufficient manner to an external actor, like a researcher, was the first big obstacle in this research. In the particular case of this research, a major part of the data required for analysis belongs to the design and feasibility study phases, which are often (if not always) highly protected and classified, sometimes with very limited access within the company. Consequently, several documents cannot be either accessed or referred for publication. Also, instead of detailed information, sometimes broadly aggregated data is provided and sometimes it is not clear how “fresh” or consistent is the data.

Conducting research with multiple case studies can also face limitations. Publications I, II and IV involve multiple case studies of barriers and drivers for eco-design implementation. While the involved pulp and paper companies are more open to discuss about progress and drivers, they also tend to be reluctant to disclose barriers, as disclosing barriers are perceived as potentially providing to competitors some kind of information advantage. Thus, research on barriers with companies develops as a “trust exercise” that faces limitations in the form of lack of transparency from the companies. Also regarding multiple case studies, the main limitation of the combination of Boolean Logic with DSM is that the number of potential combinations of a cell grow exponentially at a $2^n$ factor (where “n” is the number of case studies). Because of this, up to four cases in parallel can be analyzed without complications manually. However, for more than four cases further computational assistance is required.

Another limitation is that the work can be rather conceptual. Particularly for Publications II, III, V and VI, new techniques were derived from combinations of methods that had never before been mixed in the literature. While the arguments behind the idea of each case of integration of methods is well-established and corroborated with results, both the results and the analysis are still strongly data-dependent. Nevertheless, higher accuracy of data, though it could potentially change the results, it would not change the proposed innovative techniques. An example of this is Publication V, which for the reliability of the analysis, extensive tests with randomly generated numbers were performed. Slightly different tendencies may appear when the method is extensively applied to real world data.

One more limitation is the contextual scope of the research. First, the case studies focused on the enhancement of decision-making, but expansion to additional fields may produce different results. Second, the case studies comprised Finnish pulp and paper companies only. While in theory the concept could be applied for decision-making in companies in different geographical areas or industrial sectors, due to the lack of data access it was not possible to validate the proposed methods outside the specific scope of the publications.

This thesis has focused mainly on large companies and only in Finnish pulp and paper industry, so the key contributions and implications cannot be fully transferred or generalized to all companies and industries in local, regional or global scale engaging
Horizon 2020, which provides an interesting avenue for future studies. In addition, the present study was conducted from the perspective of expert’s judgement involved in engineering design activities in pulp and paper industry in Finland. Other research avenue could complement the findings by seeking the perspectives of other external stakeholders to reach optimal decisions.

As mentioned in chapter 3.5 the quality of the research was achieved based on criteria such as credibility, transferability, dependability and confirmability. The credibility of the research is supported by the input from industry experts and validated by them and from several peer-reviewers of publications. The transferability of the research is limited, while in principle the developed methods can be applied in different contexts, the results have been validated only within the scope of the Finnish pulp and paper industry. Regarding the dependability, the data under analysis has been always presented, in aggregated form, throughout the publications. Access to raw data is limited, as the participation in the interviews was preceded by an agreement of anonymity. Finally, the confirmability of the research is again limited to the context of the research, as the experts who participated in the data collection validated the results obtained from the proposed methods.

Moreover, the fact that the proposed approach is validated only within the context of the Finnish pulp and paper industry provides the opportunity to explore the efficacy of the developed approach in new and different fields. The study, and methods, could further be expanded to take into account stakeholders beyond the industry experts such as government, society, NGOs, etc.

Therefore, future work can focus on the validation of the proposed methods for different activities, industrial sectors and geographical areas. The expansion of the scope could potentially highlight aspects of the proposed theories that need to be expanded in order to fit general cases. Also, additional methods could eventually be integrated to the ones presented in the dissertation, which could significantly reinforce the model and improve both the analysis and the results.
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PART II: INDIVIDUAL PUBLICATIONS
Publication I


Use of Design Structure Matrix for Analysis of Critical Barriers in Implementing Eco-design Initiatives in the Pulp and Paper Industry

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Use of Design Structure Matrix for Analysis of Critical Barriers in Implementing Eco-Design Initiatives in the Pulp and Paper Industry

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Abstract

Eco-design initiatives are gaining importance due to changing environmental conditions and the industry is developing different solutions. The purpose of this paper is the identification and evaluation of barriers related to the implementation of eco-design initiatives in pulp and paper industry. This study identifies the key barriers through literature research and provides information flow dependencies using design structure matrix through a case study of a company in Finland. This method differs from traditional management tools because it focuses on representing information flow rather than workflow. The findings provide policy recommendations to policy makers for managing eco-design implementation.

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Keywords: Eco-Design; Design structure matrix; Pulp and paper industry; Management barriers

1. Introduction

During the past two decades, the sustainability concept has gained a great importance in the manufacturing industry. This is due to continuously increasing the pressure from stakeholders, e.g., employees, investors, suppliers, customers, competitors, communities, government, regulatory bodies etc. for the improvement of the environment.

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There are current global tendencies for the improvement of environmental sustainability and minimizing the negative impacts on the environment, in other words, of sustainable development. As part of the tendency, authorities establish strict criteria and requirements for the environmental performance of companies and their products [1]. In the EU, for instance, the requirements are set in the form of directives from the European Commission [2, 3].

Sustainable product and process design aim to reduce waste, mitigate pollution and reduce health risks to humans and other species, while contributing to conserve energy and materials, eliminate toxic substances by establishing sustainable environmental, economic and social objectives [4]. Sustainable development seeks to optimize efficiency while minimizing negative environmental impacts and maintaining social equity. These represent the three pillars of sustainable development; financial, environmental and societal. It is also important to develop key performance indicators [5] for each of these three broad categories in order to evaluate the company’s sustainability performance. For example, environmental regulations in large manufacturing companies in China encourage adopting eco-design practices and use of recyclable materials and reusable parts, providing evidence that coordinating activities between eco-design and the external environment is mostly needed [6]. Therefore, adopting the eco-design initiatives for sustainable development in manufacturing is experiencing increasing importance from society, and companies seeking for sustainable manufacturing measures and environmental strategies are also becoming increasingly common.

The eco-design can extend (but is not limited to) to packaging, manufacturing and product and process design. Based on the literature review, eco-design has been adapted and included in the study, where product and design are analysed from a modern production perspective [7]. Eco-design consists of different stages [8], however, in the present study eco-design focuses on the design of new methods for product improvement, redesign tasks and derive eco-design improvement strategies. Consequently, an eco-design initiative in the pulp and paper industry is a complex system that involves many elements from various disciplines and functional areas. One of the key challenges of pulp and paper manufacturing today is to understand and optimize its environmental impact, and to identify the key barriers that hinder the implementation of eco-design. The motivation of this study is to propose and apply a novel approach that helps to identify and analyse the barriers in order to implement eco-design initiatives in pulp and paper manufacturing. The present study focuses on analysis of critical barriers for implementing eco-design initiatives using design structure matrix (DSM) based on three case studies of pulp and paper companies in Finland. The aim of this paper is to identify and evaluate the key barriers for implementation of eco-design for sustainable manufacturing in the pulp and paper industry. The research questions for this study are proposed as:

1) What are the key barriers in implementing eco-design initiatives in the Finnish pulp and paper manufacturing industry?
2) What method can be used for analysis and evaluation of key barriers for implementation of eco-design initiatives in the Finnish pulp and paper manufacturing industry?

The rest of the paper is organized as follows: a review of relevant literature discussing barriers related to the implementation of sustainable process design and manufacturing is presented in Section 2. Section 3 introduces the methodology chosen in the present study; DSM, data collection and case studies. Data analysis and results are discussed in Section 4. The paper is wrapped up with a set of policy recommendations and conclusions in Section 5.

2. Literature Review

2.1. Eco / Sustainable Process Design

Sustainable manufacturing can be defined as the creation of goods or services that satisfy the customer needs while respecting the environment and communities’ wellbeing [9]. It aims to integrate sustainability into consideration for manufacturing activities, seeking a balance between financial, social and environmental factors thought the optimization of resource use, social value and environmentally responsible practices [9].

The eco-design initiatives can target increase the efficiency of use of energy or materials, reduction of waste and emitted pollutants, reduction of hazardous materials and substances in the manufacturing process, improvement of waste handling protocols or techniques, recycle and reuse, utilization of greener technologies and materials, etc. to mention some [10, 11]. Intense investment and strong commitment, both internal and external to the company, are
required to develop the human resource capable of deploying eco-design practices [12].

2.2. Barriers to eco-design initiatives in sustainable manufacturing

There are several barriers that even successful companies encounter in their eco-design initiatives’ deployment. The idea of eco-design initiatives is relatively new [13], and many of the barriers involve integrating sustainable manufacturing practices into day-to-day business operation. Training the employees on the need to change from status quo to sustainable business practices can present a difficult challenge. What has been assumed historically as a major barrier, the economic cost, has turned out to be less of a hurdle when companies realize the economic benefits associated with sustainable manufacturing practices.

Within the European context, the advanced technologies and highly trained working force are matched with tighter regulations. Hence, the context to which Finland is exposed is very specific, even within the region. From literature, a selected list of key barriers identified for the context of pulp and paper manufacturing in Finland are presented in Table 1. The barriers presented are the factors, which are considered the main obstacles to the implementation of eco-design initiatives in the Finnish pulp and paper industry, for companies that, either following tightening regulations or as part of ecological strategy, seek higher sustainability scores [14]. The importance of the key barriers for implementation of eco-design initiatives generally can be validated from expert’s inputs. In terms of adopting eco-design initiatives for implementation, different industrial organizations deal with different barriers in various ways. Nevertheless, barriers that have direct impact in implementing eco-design process must be identified.

The 12 existing key barriers that affect implementation of eco-design initiatives in sustainable Finnish pulp and paper manufacturing industry were identified and collected through research and validated through expert’s inputs and interviews, and are presented in Table 1. The identified barriers were categorized in four major groups, which include institutional, management, technology and stakeholders and declared as system elements.

Table 1: Identified barriers affecting the implementation of eco-design initiatives in the supply chain of manufacturing company

<table>
<thead>
<tr>
<th>ID</th>
<th>Cateories</th>
<th>Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Institutional</td>
<td>Lack of coordination from academic experts for implementation of eco-design process initiatives</td>
</tr>
<tr>
<td>B2</td>
<td>Lack of support from institutions for commercialization of cleaner production technology</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>Complexity in monitoring suppliers’ environmental practices</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>Lack of customer awareness on eco-design initiatives</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>Lack of internal coordination on eco-design investment</td>
<td></td>
</tr>
<tr>
<td>B6</td>
<td>Lack of employee involvement in eco-design initiatives</td>
<td></td>
</tr>
<tr>
<td>B7</td>
<td>Lack of top management encouragement for training initiatives on eco-design process</td>
<td></td>
</tr>
<tr>
<td>B8</td>
<td>Uncertainty in product demand</td>
<td></td>
</tr>
<tr>
<td>B9</td>
<td>Lack of capital investment opportunities for green process</td>
<td></td>
</tr>
<tr>
<td>B10</td>
<td>Lack of coordination from customer on eco-design process</td>
<td></td>
</tr>
<tr>
<td>B11</td>
<td>Lack of buyer/customer knowledge on eco-design initiatives</td>
<td></td>
</tr>
</tbody>
</table>

3. Methodology

3.1. Solution Methodology

A DSM is an efficient and commonly used method of showing the interdependency relationships among the design activities in a project [15]. DSM, introduced by [16], is a new paradigm that works from the structure of the information flow inherent in the problem. It is a qualitative, straightforward and flexible modelling technique for designing, developing and managing complex systems. DSM enables the representation of complex problems, using
a number of element dependencies, which are permitted to assume the relationship, interaction and interdependencies between them [17]. DSM, associated with a directed graph is a binary square matrix with \( m \) rows and columns, and \( n \) non-zero elements, where \( m \) is the number of nodes and \( n \) is the number of directed lines connecting these nodes in the directed graph. In DSM rows and column is corresponding to the design activities [16].

Given a set of \( n \) activities in a project, the corresponding DSM is an \( n \times n \) matrix where the project activities are the row and column headings listed in the same order. The precedence relationships among activities appear in the off-diagonal elements of the matrix. If activity \( j \) depends on activity \( i \) (that is, \( i \) feeds \( j \)), then the value of element \( ij \) (column \( i \), row \( j \)) is one (or flagged with a mark such as “X” or “●”) in a binary DSM. Otherwise, the value of the element is zero (or left empty) [18]. If the activities are executed in the same order as they appear in the DSM, then marks below the diagonal represent forward information from activity \( i \) to \( j \), while those above the diagonal represent feedback information from activity \( j \) to \( i \). The DSM can be define as follows:

**Definition 1.** Let it be the DSM with square matrix, \( n \) denotes the number of activities. DSM is binary Boolean matrix \( A = [a_{ij}]_{n \times n} \). Its element \( a_{ij} \) can only be “0” or “1”. Thus, it can be defined as

\[
a_{ij} = \begin{cases} 
0 & (i = j \text{ or } a_{i} \rightarrow a_{j}) \\
1 & (a_{j} \rightarrow a_{i}) 
\end{cases}
\]  

In the matrix, the element \( a_{ii} = 0 \) is on the diagonal. In addition “\( a_{i} \rightarrow a_{j} \)” denotes that activity \( a_{i} \) input information to activity \( a_{j} \), then \( a_{ij} = 1 \), otherwise \( a_{ij} = 0 \) [19].

DSM method has been largely applied in the literature. It enables to improve the system structure by using matrix-based analysis techniques. DSM has been used for the analysis and improved understanding of complex systems, and applied in various fields including automotive [20], aerospace [21], construction and telecommunications [22], policy formulation [23], planning and operation management [24] and supply chain [25], among others. DSM model is used as a solution methodology in this work. It assists in decomposing, organizing, analysing and improving a complex problem. The method requires a cycle of analysis and a number of iteration steps. The DSM model shown in three case studies represents the barriers for eco-design practices launched since 2004 for the pulp and paper manufacturing industry in Finland as explained by the managers interviewed. The “ProjectDSM” software version 2.0.1 was employed to analyse the sequence of the information flow.

To illustrate how DSM can be applied, three case studies identifying and analysing the key barriers from the domain of pulp and paper manufacturing industry in Finland are presented. These case studies are exploratory because they are focused on implementing environmental strategies in a large-scale investigation. This helps to identify questions and select types of measurements prior to the main investigation. Although these issues are listed as a sequential step in the DSM modelling process, in a real world company the process of eco-design initiatives is quite complex.

### 3.2. Data Collection

In the first step, during the research phase, semi-structured interviews and documentation for the identified barriers through information system, annual reports and internal and external documents of the company were the information source used to identify and describe the current situation of the eco-design implementation process. First author was involved in data collection and interpretation. Next, the identified barriers through above-mentioned literature review were presented to industry experts to have their evaluation. The evaluation includes determining the strength dependencies and interdependencies related barriers. Nine interviews with managers and decision makers were conducted, all of them key decision makers involved with either development or implementation of eco-design initiatives. In addition, workshops held for implementing eco-design initiatives took place. Therefore, nine specialists from different areas (as are: director of strategic planning and decisions, vice president for sustainability, manager of environmental protection, manager of re-source platform, project manager in product safety/environment and responsibility team, planners and technical experts), have a rich knowledge and, each with
over ten years of work experience in the pulp and paper industry participated in the workshop. Through the interviews and workshops, the identified barriers were updated and evaluated based on the interactive cycle for their interdependent relationships. The multidisciplinary experts’ team then validated the barriers and the strength of the interaction dependencies.

3.3. Case Study of Finnish pulp and paper industry

The current case study was performed in the period of three months from January to March, 2017. The companies addressed in the case studies deal with the manufacturing pulp and paper products located in southern Finland. The target of the case studies analyses is to provide a set of appropriate policy recommendations in order to promote the implementation of sustainable practices. Wood processing, to produce a wide range of products from planks to pulp and paper, remains one of the largest industrial sectors in Finland. The pulp and paper industry in Finland, is today one of the world’s leading pulp and paper producers and wood processing. The companies have strategic targets of improving the performance of eco-design process through their business activities and identification and evaluation of the existing barriers is the first step to reach those targets. Policy makers and managers are looking to implement different types of eco-design initiatives and different approaches in order to achieve sustainability in a modern manufacturing company. In all cases, companies have received awards and public recognition for their commitment and intensive action related to sustainability. The cases are listed in Table 2, which presents some details of the interviewed experts of the industry in Finland. The experts from three companies, labelled cases A, B and C, represent the three largest pulp and paper and wood processing consortiums of Finland, and all of them are decision makers in matters of environmental management, hence making the analysed sample very relevant to the Finnish pulp and paper industry.

Table 2. Demographic details of interviewed experts in Finland

<table>
<thead>
<tr>
<th>Company</th>
<th>Project</th>
<th>Examples of company activity type</th>
<th>Example of quality certifications</th>
<th>Example of expert title and responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company B</td>
<td>Packaging, biomaterials, wood and paper</td>
<td>ISO 9001, ISO 14001, OHSAS 18001 as well as PEFC™ and/or FSC® Chain of Custody</td>
<td>Vice President, Sustainability team</td>
<td></td>
</tr>
<tr>
<td>Company C</td>
<td>Producer of graphic papers and suppliers especially papers</td>
<td>ISO 14001, EMAS ISO 9001 OHSAS 18001 ISO 50001 EES+ Chain of custody PEFC, FSC EU Ecolabel (Copying and graphic paper, Newsprint paper)</td>
<td>Manager, Product Safety, Environment and Responsibility team</td>
<td></td>
</tr>
</tbody>
</table>

4. Data analysis and Results

After collecting data, the DSMs are built. First, the barriers are represented and mapped in a 12 x 12 square DSMs, where these elements/barriers are listed on the left side of the DSM. Next, input information dependencies between each of the identified barriers were defined in the software based on the experts’ inputs. Based on the barriers interactions, then the DSM graph structure is analysed. One of the key insights resulting from the DSM model is to see the planned and unplanned iterations.

In binary DSM notation (where the matrix is populated with black dots and empty cells) listed in the matrix, a single attribute was used to convey relationships between different systems elements; namely, the “existence” attribute which signifies the existence or absence of a dependency between the different elements. The pink shaded boxes along diagonal represent planned iterations and the black dots represent present iterations. This means that planned iterations are the parts of the process where work across several related activities (barriers in this case) is required in order to reach the optimal state from the first attempt. Next step, an analysis of the created DSM and
optimized dependency sequence algorithm within iteration blocks was performed. The DSM optimization algorithm consists of sequencing and clustering. While sequencing is used to reduce iteration and sequence better the process flow of elements (e.g. processes, information flows), clustering is applied to create element groups that have strong internal and few external connections [18]. Analysing the process flow of the elements in the DSM, shown in Figure 1, presents the elements (in this case barriers) and their dependencies and interdependencies after clustering in the optimized matrices for cases A, B and C respectively as indicated. The analysis identified the multidisciplinary interactions (shaded in pink), which occur between different categories. The different cases in Figure 1 show that implementing eco-design process involves different coupled blocks (or chunks) in design workflow. However, there are used different coupled blocks of information feedback to replace the initial complex design process.

In Figure 1 is shown that even though barriers analysed for all case studies are the same, the distribution and sequence of the dependencies is quite different. This can be explained by the fact that the perception or effect of the barriers depends on many factors specific to the company, such as organizational structure, company size, or even geographical location, among others. Nevertheless, the interactions specific to each company are out of the scope of the presented research. Instead, the focus is given to the barriers that share correlations in between companies, and hence can be considered as barriers for the industry.

Shown in Figure 1 are the shaded blocks that represent critical dependencies. Critical dependencies require especial attention from the managers, and are often mutual (interdependent). It can be also noticed that the barriers which dependencies are common between companies, highlighted by the added circles, where green indicates a dependency common for all cases and blue circles represent a shared dependency in between two cases.

The dependency of barrier B7 to barrier B8 (both from management category, marked with green circle for all cases), though is the only one present in all case studies, its appearance within the cases differs from case to case. For cases A and C, the dependency of the barriers appears below the diagonal, which means that the relationship of barrier B7 to B8 is perceived as independent to all other barriers. However, for case B barriers B7 and B8 are critical and interdependent of each other. Translated to natural language, it makes perfect sense, as the lack of employee involvement in eco-design practices can always be explained by a lack of encouragement for training from top management, but they can also be mutual.

The correlation of barriers B5 and B6 is perceived as critical and interdependent of each other for cases B and C (marked with blue circles). It is quite revealing that though both belong to the same category, it is clear that B5 is external and B6 is internal to the companies, nevertheless they are interdependent. Again, in natural language it makes sense, since many external factors act as drivers for eco-design implementation (e.g. customer demand, government regulations, certification requirements, etc.). When an uninformed external factor (in this case customer) does not provide a clear target for investments on eco-design to be made, a barrier is faced. But also, hesitating eco-design investments from the company side are not clearly perceived by a customer, hence they can be unnoticed by the later.

Similarly, the correlation of barriers B1 and B4 is common for cases A and C, but in different ways for each case. In case A, the correlation appears as independent and does not seem to interact with any other barrier. However, in case C this correlation appears inside a criticality (shaded) block, and above the diagonal. In other words, for case A it seems as if the lack of coordination of academic experts is only related to the complexity of monitoring of
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provider’s practices, while for case C it seems to be the other way around, as if the complexity of monitoring provider’s practices hinders the coordination of academic experts. In reality, as field under continuous development, it makes sense that in different situations the monitoring of provider’s practices and academy may sometimes bottleneck each other over a developing technology, for example.

Finally, the correlation of barriers B2 and B8 appears in common for cases B and C. In this case, both cases perceive the correlation as independent and non-critical, unrelated to other barriers. Again, back to natural language, it makes perfect sense that the lack of support from institutions for the implementation of cleaner technologies to hinder the top management support for eco-design trainings, as new cleaner technologies are very often (if not always) the target of eco-design related trainings.

Overall, it is clear that achieving eco-design initiatives in a pulp and paper manufacturing company is not possible without strong governmental support and related policies. Therefore, the role of institutions is crucial for enforcing industries to promote the targeted activities, especially in the case of green technologies that support environmental improvement in a long-term life cycle perspective. Overall interactions in all abovementioned cases are called interdependent information flow. Managers should increase attention to the feedback of information flow in these blocks and should estimate the complicity level between related design activities. In addition, usability of DSM in capturing and evaluating the barriers in eco-design process in Finnish pulp and paper industry, undoubtedly, can clearly recognize the complex relationship between the coupled activities.

5. Conclusions

The aim of this paper was: 1) to explore the main barriers related to implementation eco-design process in Finnish pulp and paper industry and 2) to utilize DSM to tackle the identified issues. The objective was not to identify only a large number of barriers to implementing eco-design practices in the companies. Instead, the aim was to capture and analyse the critical barriers, and their interactions, that the companies have in common and therefore affect the pulp and paper industry in Finland related to environmental strategic objectives.

The method shows a great efficiency in eco-design analysis and as a new way to effectively manage the large-scale systems such as sustainable manufacturing. The analysis results indicate that the main barrier correlation for implementation of eco-design initiatives in Finnish pulp and paper industry are barriers B8 ‘Lack of top management encouragement for training initiatives on eco-design process’ with barrier B7 ‘Lack of employee involvement in eco-design initiatives’ from management category. Another barrier correlation very relevant for the industry is the interaction between barriers B5 and barrier B6, both critical for case studies B and C. Furthermore, common barrier correlations for the industry are barrier B2 with barrier B8, and barrier B1 with barrier B4. It requires more attention for further improvement. The results of this study also have shown that lack of collaboration between the company’s management and the government institutions remain the main obstacle in achieving implementation of eco-design initiatives. It can be concluded that an intensive collaboration between academic research institutions and industrial organizations could enhance the potential for systematic investigation of new product design and their market development strategy to overcome barriers and facilitate decision-making in the pulp and paper sector.

The main contribution of this paper is to present the identification of potential barriers for implementing eco-design initiatives in the Finnish pulp and paper industry and structure those into four main categories. Next, clustering and systematic analysis of barriers through DSM has brought changes and mix interactions for each barrier. The proposed method provides insights into the process structure, identifies problem areas in processes and enables process re-designing. Systematic analysis of three case studies in this paper has significant managerial implications. DSM methodology used in this study provides managers in Finnish pulp and paper industry with deeper insights of the different barriers, which should be considered, while adopting eco-design practices.

In line with the current literature about strategy development, business environmental goals and improvements of performance indicators and their effectiveness for sustainable manufacturing, the presented DSM analysis highlighted barrier interdependencies between the institution, management, technology and stakeholders. Finally, the improvement of eco-design initiatives happens through the design activities and development of legal framework for the establishment of clean and green technologies, which play a crucial role in the commercialization of products
in order to reach maximum benefits from sustainability practices. Furthermore, from the evaluations of barriers for adopting eco-design initiatives in Finnish pulp and paper industry to determine their dependency strength using DSM, it was possible to develop and propose the following set of policy recommendations and related environmental strategies to address the barriers.

- Development of the strategic policies for long-term investment in green technology for sustainable process and product development.
- Companies need to focus on the product stewardship, which includes a wide range of sustainability practices from product design to supply chain.
- Management and decision-making body in manufacturing companies need to integrate programs for monitoring activities in eco-design process throughout the supply chain.
- Development of environmental training programs and activities for workers in the production departments.
- Involvement of all staff levels in the environmental training events for integrated programs in adopting eco-design initiatives.
- Extension of internship programs for students and researchers to strengthen academic collaboration.
- Development of interdepartmental communication channels for coordination of eco-design implementation.

Since this study was the first attempt to use DSM for identifying key barriers in eco-design initiatives for the Finnish pulp and paper industry, there are some limitations that require further research. First, the identification of the barriers was based on interviews and experts’ knowledge, which was not completely structured. This limitation can be overcome by considering the extended list of policy recommendations with detailed guidelines in each barrier to be carried out in the next stage of the research. Second, the scope of this study is limited only to the current Finnish geographical, political and economic situation.

The future research extension will focus on integrating DSM with ranking methodology in order to show which barrier has priority within a cluster and to quantitatively evaluate the implementation of eco-design initiatives (i.e. benefits on time, cost benefits, effect relevance and technical complexity) in order to remove some of the inherent vagueness and uncertainty.

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References

Publication II


Overview of the interdependencies of barriers for implementing Eco-Design initiatives: DSM and Boolean visualization approach

Edited by Katja Höltä-Otto, Tyson R. Browning, Steven D. Eppinger and Lucia Becerril (Eds.)

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Overview of the interdependencies of barriers for implementing Eco-Design initiatives: DSM and Boolean visualization approach

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²Faculty of Process and Environmental Engineering, Lodz University of Technology, Poland

Abstract: This paper presents an overview of barriers for eco-design implementation in Finnish pulp and paper industry, using design structure matrix complemented with a new proposed Boolean logic, aiming to support the identification, comparative analysis and improve the visualization of results. The usefulness of the proposed approach is shown by taking three Finnish companies as case studies. According to the findings, the common barrier correlation in the industry implies that the barriers “Lack of employee involvement in eco-design initiatives” and the barrier “Lack of top management encouragement for training initiatives on eco-design process” are strongly related for all studied companies in the field. This study adds knowledge into the current literature of sustainable pulp and paper manufacturing and provides insights to managers and practitioners in terms of managing eco-design implementation in an efficient and effective manner.

Keywords: Eco-design implementation, pulp and paper industry, barrier interactions, DSM, sustainable manufacturing

1 Introduction

The concept of eco-design in the manufacturing industry has received considerable attention in the last couple decades, due to the number of various factors. Governmental regulations and stakeholders constantly pressure industries and companies to increase competitiveness, preserve the environment and improve their resource-efficiency. Therefore, eco-design initiatives are important in the search for sustainability. There is a tremendous, and increasing, interest in sustainable design (Lewis, 2012). Although some studies have analyzed barriers faced by different companies (Theyel, 2000; van Hemel and Cramer, 2002; Boks, 2006; Pajunen et al., 2012), there is still a need for further research in this issue. Moreover, no previous studies have observed the barriers of eco-design practices, where research entities have been involved for identifying and evaluating key barriers in eco-design process implementation in pulp and paper industry. In this work, some barriers to implementation of eco-design that Finnish pulp and paper companies face and the methods or tools that can be used to tackle them are examined. Furthermore, it was noticed that no research has been done specifically and explicitly in the relationship between the ability to identify key barriers with the ability to analyze and model their overlapping. Therefore, the present study focuses on answering the following research questions: (a) what are the key barriers in eco-design initiatives for Finnish pulp and paper industry? (b) Which are the methods and tools to be used for better
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visualization of overall barriers and their improvements for implementing eco-design initiatives? (c) What is the practical applicability of the proposed method to be developed and used in the context of the Finnish industry?

To answer the mentioned questions, design structure matrix (DSM) is complemented with Boolean logic to analyze in parallel three case studies of pulp and paper companies in Finland. This research: (i) Identifies key barriers for implementation of eco-design initiatives in pulp and paper industry, (ii) Finds out the interaction and interdependences among the barriers using DSM, in order to better understand and analyze the problems related to eco-design issues, (iii) Conducts a comparative analysis of barriers for better visualization of all cases in parallel in one DSM through Boolean logic approach, (iv) Examines the effectiveness of the proposed method. The main contribution of this paper is the identification of the key barriers to eco-design in Finnish pulp and paper companies and to show how to apply Boolean logic for better visualization of the overall barriers. In other words, companies have their independent variables that differ from each other, while DSM tool combined with Boolean logic helps to detect and analyze the common barriers that affect the Finnish pulp and paper industry. A comprehensive overview of the identified barriers for implementation of eco-design initiatives from the DSM perspective in real case studies are developed in close collaboration between Finnish companies’ management board and research institutions.

The significance of this work, and how it differs from other work, is that it tackles pulp and paper companies’ need for increasing their sustainability scores through the implementation of eco-design. This has lead companies to adapt their approach to cope with the need, and it often relates to strategies and their underlying principles and activities. DSM methodology (Eppinger and Browning, 2012) has been demonstrated to be effective to help with this optimization and better visualization of barriers in the pulp and paper industry.

This paper is structured as follows: in section 2 the state of the art regarding process/product eco-design as well as DSM method for capturing the interrelationship of barriers in eco-design implementation is presented. Section 3 describes the used research methodology including data collection and data analysis in detail. Outcomes and findings are described in section 4. Discussion, managerial implications and limitation of the proposed approach are given in section 5. followed by the conclusions and future work in section 6.

2 State of the art

Eco-design is a product design process (Glavic and Lukman, 2007; Bevilacqua et al., 2007) that describes the consideration of the ecological performance during product development, whereas the ecological performance refers to the interference of the product with the environment (ISO, 2015). Otto and Wood (2001), Billatos & Basal (1997), Lewis & Gertsakis (2001) and Thompson (1997) provide different definitions of ‘eco-design’ or ‘design for environment’. By definition, ‘eco-design’ is “the integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product's life cycle” (ISO, 2011). Labeling, sustainable reporting and marketing are some examples of eco-design applications in the
market. Law and standard regulations are developed to establish both methodologies and benchmarking frameworks (e.g. Directive 2009/125/EC /European Council, 2009), ISO 14006 (2011). For example, Ravi (2015) has reviewed the interaction of barriers through interpretive structural modeling (ISM) for eco-efficiency in electronic industry. The pulp and paper manufacturing industry, due to its strong reliance on forestry, has high dependency on eco-design, and Finland is well known for its commitment to environmental issues. Efficient use of the material resources and energy efficiency, pollution prevention, reuse and recycling help in achieving eco-efficiency in the pulp and paper industry (Watkins, 2013). There are very few research studies which have examined the critical barriers to eco-design implementation in pulp and paper industry in the context of developed countries (Thollander and Ottosson, 2008; Thollander et al., 2013; Watkins et al., 2013). Moreover, Finland has a highly educated workforce regarding sustainability and a strong entrepreneurial spirit; however, adoption of eco-design practices in pulp and paper industry is still not free from barriers. To cope with these barriers, a systematic approach is required. Twelve barriers in this study have been identified from the literature review and also from expert’s interviews, both from industry and academia.

In this paper, identification of the key barriers for implementing eco-design initiatives is state of the art. Regarding the collection and aggregation of this data, DSM and Boolean logic, are well-known established approaches, but a general procedure to integrate them is missing. Complementing DSM with Boolean logic for implementing eco-design initiatives in the development phase is lacking – especially in pulp and paper industry. Furthermore, the potential capabilities for identifying and evaluating the barriers to eco-design initiatives will be an ecological improvement of this scope.

2.1 Barriers identification in the selected companies in Finland

Finland has built up a strong forestry and pulp and paper industry, leading to a large part of Finnish exports being related to paper. An obvious strength is its ample supply of biomass since 60% of the country is covered by forest.

Table 1. Identified barriers affecting the implementation of eco-design initiatives in pulp and paper industry (Buzuku and Kraslawski, 2017)

<table>
<thead>
<tr>
<th>ID</th>
<th>Category</th>
<th>Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Institutional</td>
<td>Lack of coordination from academic experts for implementation of eco-design process initiatives</td>
</tr>
<tr>
<td>B2</td>
<td>Institutional</td>
<td>Lack of support from institutions for commercialization of cleaner production technology</td>
</tr>
<tr>
<td>B3</td>
<td>Institutional</td>
<td>Complex external institutional environment</td>
</tr>
<tr>
<td>B4</td>
<td>Institutional</td>
<td>Complexity in monitoring suppliers’ environmental practices</td>
</tr>
<tr>
<td>B5</td>
<td>Management</td>
<td>Lack of customer awareness on eco-design initiatives</td>
</tr>
<tr>
<td>B6</td>
<td>Management</td>
<td>Lack of internal coordination on eco-design investment</td>
</tr>
<tr>
<td>B7</td>
<td>Management</td>
<td>Lack of employee involvement in eco-design initiatives</td>
</tr>
<tr>
<td>B8</td>
<td>Management</td>
<td>Lack of top management encouragement for training initiatives on eco-design process</td>
</tr>
<tr>
<td>B9</td>
<td>Technology</td>
<td>Uncertainty in product demand</td>
</tr>
<tr>
<td>B10</td>
<td>Technology</td>
<td></td>
</tr>
</tbody>
</table>
Part II: DSM Applications on Sustainability

<table>
<thead>
<tr>
<th>B11</th>
<th>Stakeholder</th>
<th>Lack of capital investment opportunities for green process</th>
</tr>
</thead>
<tbody>
<tr>
<td>B12</td>
<td></td>
<td>Lack of coordination from customer on eco-design process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lack of buyer/customer knowledge on eco-design initiatives</td>
</tr>
</tbody>
</table>

However, since global demand for paper is in decline due to digitalization, the industry is under pressure to develop new products and tap into new markets. This transition is strongly connected with environmental strategies and industry’s objectives. In addition, eco-design involves incorporation of design activities, which means that needs to be proactive and innovative in order to achieve sustainable development. The main activities in this context are to identify and define the barriers that are hindering eco-design implementation. In this case, the barriers identified from the literature were presented to the experts during an interview, where the experts were further asked if there is any important barrier/driver that should be added. The evaluation of dependencies among barriers is then fully determined by the experts. In addition, these barriers were divided into four categories: institutional, management, technology and stakeholder, through experts’ judgments. The results of the barriers identification are displayed in Table 1.

2.2 Capturing the interrelationship of barriers in Eco-design process through DSM

A DSM approach has been referred as a promising approach for capturing the interactions of the elements in the system. DSM is a generic tool for modelling the constituent elements of a system and their interactions (Eppinger and Browning 2012). DSM have been used for numerous applications in research to show the dependencies and interactions between system elements, analyze iterations and rework in design, analyze change propagation, visualize interdisciplinary change impact, identify interactions within organizational structures, develop a collaboration plan and design information exchange processes, optimize design information flows, among several other applications (Austin et al. 2001; Browning, 2001; Browning and Eppinger, 2002; Eppinger and Browning 2012; Buzuku et al., 2016; Buzuku and Kraslawski, 2017). These are enabled through appropriate determination of the interrelationships and interdependencies driving the behavior of the system (Browning, 2001). These relationships can be represented with component-based, people-based, activity-based DSM types. Therefore, the DSM method is proposed to examine and analyze the deeper insights of dependencies of barriers to eco-design initiatives implementation. The fact that the same barriers were analyzed in all case companies allows the Boolean logic to improve the visualization of the overall results.

3 Methodology

It was decided to identify, analyze, visualize and compare barriers from three different pulp and paper manufacturing companies, since they all have set ambitious goals for sustainable development in national level and all three can be analyzed from the scope of
the same barriers. In order to better visualize the identified barriers for implementing eco-design initiatives, DSM as promising approach is used as solution methodology. The focus of this part of the study is to capture, visualize and analyze changes in the design pattern of human activity aligned with environmental strategy. That is, changes in the DSM workflow for better visualizations, representing different projects that are carried out after being impacted by eco-design implementation. After identification of barriers through interviews and compiling the answers into three different case studies, using both quantitative and qualitative assessment, the scenario is built to create the model to analyze the structure of pulp and paper sustainable manufacturing. This paper proposes a new approach of DSM extended with 3-bit Boolean logic, for identification, modeling and visualization of the overall barriers by multiple cases in pulp and paper industry in parallel. The method implements a three-step procedure applying DSM supplementing with Boolean logic approach as are: 1) Data collection from project cases (three in this example); 2) Sequence optimization through DSM be applied to all collected information at once; and 3) A multi-project visualization using Boolean logic approach to extract the values. Therefore, DSM is, after Boolean integration, utilized to analyze and optimize the sequence of the barriers’ order for all companies in parallel, as the software does not support any other form. Next, Boolean logic is used to extract from the binary optimized and clustered DSM and break it into the elements belonging to each case study. As a result, the project portfolio for eco-design barriers is treated as a single DSM result of the combination of all separate cases.

3.1. Data collection

This research is built on data collection about the key barriers to the implementation of eco-design practices in industry. In the primary studies described in Table 2 shows the demographic summary of interviewed companies.

<table>
<thead>
<tr>
<th>Company project</th>
<th>Company type</th>
<th>Company activity</th>
<th>Quality certifications</th>
<th>Expert title and responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Packaging, biomaterials, wood and paper</td>
<td>ISO 9001, ISO 14001, OHSAS 18001, PEFC™, FSC® Chain of Custody</td>
<td>Vice President for sustainability (1), Development manager in sustainability (1), Sustainability and corporate responsibility team (1),</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Producer of graphic papers and suppliers especially papers</td>
<td>ISO 14001, EMAS, ISO 9001, OHSAS 18001, ISO 50001, ES+ Chain of custody PEFC, FSC, EU Ecolabel</td>
<td>Product safety manager (1), Environment and responsibility team (1), Production manager and technical experts (1),</td>
<td></td>
</tr>
</tbody>
</table>
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The data collection was done through time-consuming contact-and-interview sustainability staff and other company’s stakeholders. The interviews were conducted by the first author and all were conducted between January and March 2017. From each company studied, three persons working in different positions of the organization related to eco-design initiatives were interviewed and in total 9 interviews were conducted. The selected interviewees were selected based on their in-depth knowledge of the firm’s eco-design processes and practices, and the unique perspective they could provide, in order to ensure a broader view of the economic, environmental and social benefits provided by the system.

3.2. New visualization and comparative analysis of barriers for Eco-design implementation in pulp and paper industry

The results and the process of the Boolean comparative matrix aggregation are displayed in Figure 1 (following the process arrows indicated in a) through g)) using the logic and color code presented in Table 3. The presented example resulted in seven combinations and a code/color is assigned for each combination. Out of the twelve barriers identified, D, E, F and G indicate common relationships between companies, hence they can be considered as industry-related rather than company-specific. In order to be able to visualize how barriers interact with each other under an industry scope (not only individual company), a new visualization method is proposed. The method uses 3-bit Boolean logic for concentrating the data of all cases into a single DSM (as shown in Figure 1 g) and h)), to analyze the barriers of all companies in parallel. Basically, the data of all companies is input to the DSM software as binary, and from the optimized sequence, the results are extracted using the same Boolean code.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Code</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>A</td>
<td>Green</td>
</tr>
<tr>
<td>Company 2</td>
<td>B</td>
<td>Blue</td>
</tr>
<tr>
<td>Company 3</td>
<td>C</td>
<td>Yellow</td>
</tr>
<tr>
<td>Company 1+2</td>
<td>D</td>
<td>Brown</td>
</tr>
<tr>
<td>Company 1+3</td>
<td>E</td>
<td>Purple</td>
</tr>
<tr>
<td>Company 2+3</td>
<td>F</td>
<td>Gray</td>
</tr>
<tr>
<td>Company 1+2+3</td>
<td>G</td>
<td>Red</td>
</tr>
</tbody>
</table>

3.3. Data Analysis

The data analysis involved several stages. In the first stage, the interviews from all companies were analyzed to identify the key barriers related to eco-design initiatives. In the second stage, the defined relationship of dependencies is identified for each of those barriers. In the third stage includes the presentation and evaluation of the obtained and aggregated results from DSM. After all the cases individually were analyzed, the data was then reexamined using the identified barriers of the preliminary scheme of categories.
and properties following the comparative analysis method. The resulting data provided insights on how industrial firms evaluate the barriers dependencies and interdependencies, and how these dependency marks were used in DSM as arguments for investigating and exploring the overall barriers. Based on the interviews, a detailed description of the input data for each company was prepared the key results are illustrated in the next section.

4 Results

This section shows the effectiveness of the extended DSM method with Boolean logic by illustrating three different case studies. Insights from DSM perspective in multiple scenarios is presented to show the proposed approach. The model presented in Figure 1 h) represents the main outcome of this research. Figure 1 g) & h) shows the concentrated data of all study cases and the value of such visualization. In the same DSM, the individual distribution of barrier correlation is shown for each case. Such visualization provides insight of barriers perceived by an individual company (when the barrier correlation is unique for the case of a company), or by the industry (when a barrier finds the same correlation in two or more cases). Figure 1 provides an overview of the overall barriers’ dependencies for all case studies in one single DSM. Since the optimization was conducted for the dependencies of all companies simultaneously, the resulting three output clusters involve all case studies at once. From Figure 1, it is possible to notice that barrier 5 “Lack of customer awareness on eco-design initiatives” and 6 “Lack of internal coordination on eco-design investment” are correlated for companies A and B (hence is marked in brown).

Following this logic, it is possible to extract the relevant barriers for a case company (which may require management attention), but also for the overall industry when the correlation perceived in barriers is reflected equally in two or more companies (which may require external address, such as legislation). For example, a common barrier correlation in the industry is marked in red “G”, which implies that B7 “Lack of employee involvement in eco-design initiatives” and B8 “Lack of top management encouragement for training initiatives on eco-design process” are strongly related for all studied companies in the field. Translating it into natural language, it makes sense that a lack of support from top management would generate a lower involvement level of the workforce of the companies. A similar assumption can be made about the cells marked with brown “D” and purple “E”, as these are also barrier iterations shared between some (but not all) companies in the study.
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Figure 1. Concentrated correlation of barriers in one DSM using the new proposed visualization.

5. Discussion and managerial implications and limitations

With the improved visualization, it is possible to detect specific barriers of a company, it is necessary to concentrate on the common barriers due to their influence for all companies. The results show that comparative analysis between different barriers under each category as well as barriers relationships suggests several implications for managing the eco-design implementation issues. As a central contribution among the obtained managerial implications is to facilitate the decision makers and industry’s managers to become aware and take into high watch overall barriers that affect the industry. Managers are able to define interaction of barriers within their organization and to show which barriers require more attention and which barriers may be of less significance. This interaction of dependencies assists managers allocate resources appropriately. After identifying the barriers and issues, the decision making body will be able to tackle the
barriers for implementing eco-design initiatives. This study proposes a novel to explore, analyze and visualize barriers dependencies. The proposed method 3-bit Boolean logic may facilitate designers and managers to better visualize the overall barriers in one DSM from different industry scenarios. Furthermore, the combined methods are effective for providing important insights and supporting for decision-making. This study helps managers to a better understanding of the link between key barriers and the performance of eco-design practices. The results revealed that barriers “lack of employee involvement in eco-design initiatives” and “lack of top management encouragement for training initiatives on eco-design process” market in red color (see Fig. 1) are strongly related for all studied companies in the field.

In this study, some limitations require further research. First, in the identification of the barriers it was found not all possible barriers are presented in this study. For example, barriers as: high capital intensity, large production facilities and volumes, bulk products to business to business markets and large transportation volumes are considered as barriers to eco-design in Finnish forest industry. These limitations can be overcome by including the elements into DSM model in further interviews. Second, the adopted Boolean method is not optimal for more than four case studies in parallel because the generated number of combinations is $2^n$ (where “n” is the number of cases addressed in parallel). Four cases would already generate 16 different combinations, still manageable with letters and colors. The absolute limit may be 8 as $2^8$ which means a number of 256 it is close to the limit of ASCII symbols and the usual size of the extended color matrix. For an extreme case of eight parallel cases, the colors are already too similar for consecutive values, making difficult to differentiate. Other computer aided design techniques are highly recommended is such situations. Third, the proposed approach has been tested and validated in the regional and national level in Finland, while the effectiveness, reusability and usefulness is yet to be applied in different sectors in international and global level, though in principle should work. Fourth, the utilized DSM software (as indicated in section 3) is limited to binary layouts. A more advanced software could consider factors, to assign priority or weight to the barriers according to their individual nature or to their common interactions in between cases.

6. Conclusions and Outlook

The aim of this paper was i) to identify the key barriers related to the implementation of eco-design initiatives and ii) to propose a systematic approach using combination of DSM with Boolean logic for better visualization of barriers for three cases through a single DSM. The research presents a multi-scenarios modeling approach applied to the Finnish industrial pulp and paper industry, in order to facilitate not only the identification of the barriers, but also the better visualizations of the overall barriers inside a single DSM. It also finds out what are the common barriers between case studies using the proposed method 3-bit binary Boolean logic.

Overall results of the barriers in the presented study show that it is possible to achieve a multifaceted and enriched visualization perspective. The proposed systematic approach has been proved to be useful research method to accompany the updates and improvements of the company’s existing barriers in multiple scenarios. The effectiveness...
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of the proposed approach, which was implemented in three case studies in pulp and paper manufacturing industry, can solve the interrelated barriers and offers comparative analysis by incorporating as interdependent relationships of various influencing barriers as well the common barriers in one matrix. The results can be used by companies to enhance their sustainability performance. Furthermore, the proposed method can be effectively applied to analyze any context where different subjects can be evaluated with the same elements (e.g. different products of a production line).

The present work opens the door for further studies on models and tools to eco-design process for future work. Finally, in the future studies, the identified barriers for implementing eco-design initiatives can be analyzed using other decision-making methods like ranking methodology, and other commonly used multi-criteria decision-making (MCDM) in combination with DSM. Next, the extension of this work is in the development stages in the upcoming article. Another future research can focus on developing a computer simulation model to quantitatively evaluate the impact of barriers for eco-design performance measure, knowing that the barriers themselves could be weighted using several parameters (i.e., severity, capacity of acting on them, time and cost). In addition, a set of policy recommendation will be generated and described detailed guidance to overcome the barriers.

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Publication III


Supplementing Morphological Analysis with a Design Structure Matrix for Policy Formulation in a Wastewater Treatment Plant

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Supplementing Morphological Analysis with a Design Structure Matrix for Policy Formulation in a Wastewater Treatment Plant

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Abstract: Morphological analysis (MA) and Design Structure Matrix (DSM) approaches are methods that have shown their potential for modeling complex systems, including environmental management. We argue that two methods can be integrated to tackle complex problems as two phases for modeling and design of policy. The goal is to exploit the benefits of both methods and combine the two approaches into an integrative framework. The strengths of MA lie in formulating, structuring, linking and evaluating possible combinations of the variables given in the problem. DSM models the interconnections and interdependencies of these variables in a quantitative manner. First, we summarize the limitations of MA while showing avenues for its integration into DSM. We then introduce an integrated MA and DSM framework that allows designers to confront the complexity of systems modeling for public policy related to a wastewater treatment plant. A case study illustrates the integration these methods in this domain.

Keywords: Morphological Analysis, Design Structure Matrix, public policy, problem solving, complex systems

1 Introduction

Policy formulation is the development of effective and acceptable courses of action to address items on the policy agenda. It can be considered one of the most challenging tasks of the policy process and it underlies the explicit actions of policy design (Birkland, 2005). The policy context of this study, environmental policy management (EPM), of which policy formulation is a key stage, is a complex multi-dimensional problem involving many stakeholders and organizations, often with overlapping roles (Flüeler, 2006). Policy formulation for EPM can thus be considered as having the characteristics of a complex system (Sokolova and Fernández-Caballero, 2012).

Modeling complex systems such as policy formulation is a difficult and time-consuming task for practitioners, especially those that do not have sufficient knowledge of and training in use of the diverse modeling methods available (Eppinger and Browning, 2012), including the modeling methods discussed in this paper – morphological analysis (MA) and design structure matrix (DSM). Furthermore, various studies have highlighted that in addition to understanding of modeling methods, complex systems modeling often requires...
the development of new approaches, frameworks and theories to analyze, design and manage the systems under consideration (Danilovic and Browning, 2007).

In many cases, various support tools exist to enable practitioners to achieve their objectives, and to support problem solving in systems modeling, engineering and operation management (Steward, 1981; Steward, 2003; Browning, 2001). However, mastering and applying all the various methods, tools, frameworks and theories efficiently and effectively remains difficult (Yassine, 2004). For example, industrial water systems management, especially design, construction and operation of wastewater treatment systems, is a complex problem area requiring expert knowledge and much practical experience in the application of modeling methods and their support tools.

Within the specific context of this study, the problem of establishing a systematic integrative framework for problem solving can be stated as follows: The identification and formulation of a set of specific policy measures related to the problem of the construction, operation and maintenance of a wastewater treatment plant (WWTP), in which the dependencies and interconnections of these policies with the environmental system should support the decision making process for large-scale project engineering.

This paper is an attempt to assess the potential of integrating modeling methods in such a way that the integrated approach supports complex problem solving for environmental management systems related to public policy for wastewater treatment plants. The specific goal is to interlink MA and DSM as modeling methods to support decision-making in complex problem solving of policy formulation. In the work, we will show how the classical MA method can be used in EPM and how we can employ DSM to improve the process flow of dependencies.

A second motivation for proposing an integrative framework is related to the fact that policy formulation is a complex process involving a large number of stakeholders and many possible measures. Not much work has been done on policy formulation in EPM and, more specifically WWTP management, which makes it challenging to apply certain modeling techniques, even if the benefits are well known in other domains. Furthermore, the formulation of environmental policies involves a wide range of different non-quantifiable factors, in addition to the many individuals and organizations with overlapping roles. Problem solving becomes very difficult when the complexity of the problem, in principle, cannot be defined and described because of inherent uncertainties (Balint, 2011). In such situations, traditional methods such as MA have clear limitations. Therefore, there is an evident need to supplement traditional methods to provide an innovative integrative framework for policy makers.

Morphological analysis (MA) and design structure matrix (DSM) are modeling methods that can be systematically employed for decision support systems. Each method has advantages and disadvantages when modeling complex processes and systems. MA allows small groups of subject specialists to define, link and internally evaluate the parameters of complex problems spaces relatively easily, which enables effective creation of a solution space and construction of a flexible inference model. However, MA cannot easily treat the interconnections and dependencies of the variables. DSM enables modeling that not only considers the connections among the variables but also considers the connections and dependencies of these variables in a quantitative manner.
DSM is, however, difficult to employ in the initial problem formulation phase of the modeling process. This paper proposes combining MA and DSM to better facilitate modeling procedures in problem solving of complex systems such as those found in environmental management. A practical case study involving sequential use of the two methods is presented. The case study considers a wastewater treatment plant (WWTP) – a specific application in the field of environmental management.

2 Applying MA for Policy Formulation

This section discusses the application of MA to policy formulation and some weaknesses of the approach are highlighted based on the example of a case study related to a large industrial wastewater treatment plant (WWTP). The case study considers the design, procurement, construction and operation of an industrial wastewater treatment facility. The decision-supporting tool for the wastewater treatment plant (WWTP) is applied to an integrated pulp and paper mill in the Mato Grosso do Sul State in Brazil. The decision-making can be classified as a complex problem because of the capital and operational costs involved, and because the activity occurs on a federal river forming a border area between the two states of Mato Grosso do Sul and Sao Paulo.

MA was applied with the participation of a panel of experts of diverse backgrounds and specializations. Eight specialists from different fields of social, natural and engineering sciences took part in a two-day workshop. The workshop produced a set of policy measures reduction model, which allowed modelers to compare different policy options in terms of sustainability planning and implementation. Subsequently, a morphological field/space was developed based on five identified parameters and their range of values, shown in Figure 1.

![Figure 1. Morphological field for five parameters and their range of values](image-url)
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The policy formulation, as previously mentioned, was explored by the combination of values of the variables. For instance, if \( P_1V_1 \) Brazilian Environmental Law, Conama 20 is selected, \( P_1V_1 \) thus shows highest priority among the others policies and is found to be linked closely with a combination of other alternatives in a morphological field: \( P_1V_1 = (P_2V_1, P_3V_1, P_4V_3, P_5V_1) \) and \( P_1V_1 = (P_2V_1, P_3V_1, P_4V_3, P_5V_3) \).

3 Applying Design Structure Matrix

The previous section showed how MA was used. Here, we illustrated how DSM was applied in conjunction with MA. An overview of the integrated MA and DSM process is given in Figure 2.

3.1 Where DSM can supplement MA

The first stage consisted of the identification and formulation of a set of specific policy measures related to the problem of wastewater treatment plant. As discussed in the previous section, MA was used for the formulation, structuring, linking and evaluation of the possible combinations of the variables in the problem. Policy formulation in wastewater treatment is a problem for which many possible solutions exist. MA helps in determination of all possible combinations of input variables and subsequent identification of the most promising solution. The identified policy measures were transformed into criteria, which were categorized and used in the morphological analysis tool to build the morphological field.

The second stage consisted of reorganizing and improving policy process understanding via diverse iterations. The DSM model shown in Figure 3 represents a set of environmental policy measures process sequence relating to WWTP. For instance, a policy set is considered to be P1V1 with \((P2V1, P3V1, P4V3, \text{ and } P5V1)\) and P1V1 with \((P2V1, P3V1, P4V3, P5V3)\) where P1V1 shows high potential priority for WWTP. The results were formulated and composed in the presence of the panel of environmental experts engineers and managers that we interviewed.

A policy set of P1V1 with their combinations was extracted from the MA and transformed into activities of the DSM model for further investigation. The DSM model contains 5 activities, which are derived from the MA matrix by exploring the best combinations of policy measures in the domain of WWTP. These policies are listed on the left side of the DSM. In the DSM matrix in Figure 3, the pink shaded boxes along the diagonal represent planned iterations and the black dots represent potential iterations. Marks in the matrix with the black dots listed nr.3 in sequence indicates that is not planned for iterations. This means that with the exception of the policy (activity 1) Environmental Law Requirements, all the others policies need reorganization and improvement. Use of the DSM software tool allows reorganization and improvement of the process illustrating the policy formulation in the early stage of the construction and operation of the WWTP.

The last step is visualization and analysis of the best alternatives to reduce the process costs, time and risk. In the analysis it became clear that some of the policies were not well designed and could not be implemented without implications for other elements of the
Additional data are required to analyze and calculate process cost, time and risk. Due to a lack of data in this segment, the validation of the model is planned for future research, in collaboration with environmental experts, engineers and managers, to discuss and assess the policy process in the model, as well as the budgetary implications. Data needed for the calculation of capital cost and operation cost, duration and risk were not presented in the case study of the WWTP project.

3.2 Specific Contributions of DSM to MA

Once the optimal combinations have been derived using MA, it is necessary to integrate them into DSM for analyzing and modeling of the process flow of the dependencies/variables. Figure 3 illustrates a set of the best policy selection $P_1V_1 = P_2V_1; P_3V_1; P_4V_1; P_5V_1$ for the integrating of the most suitable policy in a square matrix before clustering. It enables the interconnection and manipulation of the variables and allows suggestions for improvements to the policy process to be derived. DSM is a very powerful tool for visualizing and screening out the dependencies. Consequently, the set of policy measures becomes the following: 1) $P_1V_1 = P_2V_1; P_3V_1; P_4V_1; P_5V_1$; and 2) $P_2V_1; P_3V_1; P_4V_3; P_5V_3$. In both models, it is possible to enter inputs and outputs. The ability to estimate values (or variables) and highlight interdependencies between them is a great advantage in construction of the DSM.

![Figure 2. DSM before clustering](image)

The screening mechanism was constructed and implemented using ProjectDSM v2.0 project planning software (www.projectdsm.com), which provides an automated DSM optimization step for triangulation of the DSM. Analyzing the process flow of the policy in one DSM, as in Figure 4, shows elements/policies and their interdependencies after clustering in the original matrix. For the case under consideration, analysis of this DSM indicated two clusters, each of which was then defined as a development process flow of policies. Here, we can clearly see that two shaded blocks along the diagonal were defined based on interdependencies. This helps with identification of some of the gaps between policy formulation and implementation that generally requires reorganizing policies with stakeholders. Furthermore, as we can see from Figure 4, $P_1V_1$ (Environmental Law Requirements) has the highest priority among the policies. From the expert point of view,
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the other designed policies have to follow the legislation underlying the Environmental Law Requirements.

![Figure 3. DSM after clustering the matrix](image)

4 Towards a Framework for MA and DSM integration

4.1 Weaknesses of Morphological Analysis

MA has been widely used as a general method for formulating, structuring and studying complex problems (Zwicky and Wilson, 1967). MA is based on the “divide and conquer technique” (Levin, 2012), which tackles a problem using two basic approaches: “analysis” and “synthesis” – the basic methods for developing (scientific) models (Ritchey, 1991). The MA techniques is a decomposition method that breaks down a system into subsystems with several attributes and selects the most valuable alternative (Yoon and Park, 2007). In other words, MA systematically categorizes the possible combinations of subsystems. MA has been applied in many fields: jet and rocket propulsion systems (Zwicky, 1969), computer-aided design modeling (Belaziz et al., 2000), language modeling (Huckvale and Fang, 2002), mathematical modeling (Arciszewski, 1987) and technology forecasting (Wills 1971; Yoon and Park, 2005). Carson (1979) applied MA to the development of new chemical products. In the U.S., MA was first described by Allen (1952, 1962) and later developed by Grant (1977) for application in architecture and urban planning. Morphological models were used by Carson (1974) in the three-dimensional version for modeling business capabilities in industrial organizations. In addition, Gregory (1974) and Cross (1975) developed morphological analysis for application in architecture design, while Norris (1963) applied it to engineering design.

In all these domains MA has been a powerful tool for linking and evaluating possible combinations of the variables in the given problem and for establishing an internal structure, based on iterative cycles of analysis and synthesis, in a systematic manner. Moreover, MA provides a strong possibility of generating unexpected combinations of policy measures. The weaknesses of MA lie in its treatment of the interdependencies and
that combinations of variables are manipulated in a non-quantitative manner, as well as in
the screening and selection of the most satisfactory combinations. MA therefore requires
support from others processes (Yoon and Park, 2005).

Criticisms of the MA method that have been highlighted in different fields include, for
example:

1. The non-quantitative nature of MA in treating the interdependences of the
variables.
2. Ambiguous, incomplete and often difficult to understand formulations of the
morphology used in different domains.
3. Difficulties with including the static analysis modeling of the variables and their
values in the problem space.
4. Problems with prioritizing alternatives when establishing the morphology of the
solution space of public policy.
5. Issues with defending and evaluating different parameters against each other and
generating conditions within the problem space.

Despite the obvious of MA, there is a need for further development when aiming to extend
MA to different domains. In this work, DSM is integrated with MA as a screening and
visualizing tool to evaluate some of these limitations.

4.2 Strengths of DSM and Avenues for MA and DSM Integration

Design Structure Matrix (DSM) is a straightforward and flexible modeling technique that
can be used for designing, developing and managing complex systems. DSM is a method
that has shown its power in product architectures, organization structures and process
flows (Eppinger and Browning, 2012). It enables the deconstruction of the organizational
and functional components of a system by eliciting the relationship between components
in ways that make trade-off analyses more understandable and manageable. Eppinger and
browning (2012) described the steps of system modeling using DSM as being: (1)
decompose, (2) identify, (3) analyze, (4) display, and (5) improve.

The primary difference between the two approaches, MA and DSM, is that the benefits of
the classical MA technique lie in its ability to provide structured models for complex
problems by reducing them into simpler problems (Pidd, 1966), whereas DSM is a more
basic matrix representation where the elements of the matrix represents the dependencies
between the elements of the system. In principle, both methods are based on “divide” and
“conquer”. Moreover, both MA and DSM are qualitative methods that depend on expert
opinions and judgments. DSM is essentially a more analytical approach to system design.
DSM is a more general method because it considers representations of systems rather than
only relationships between individual components (e.g., individuals in social networks).
Figure 4 portrays the limitations of MA, the strength of DSM, as well as avenues for
integrating these two methods into a single framework for formulation of public policy
and resolution of complex problems.
5 Conclusions

This paper illustrated how DSM integrated with MA could be used in policy formulation. The weaknesses of MA were presented and it was shown how DSM could supplement MA in the formulating, structuring, linking and evaluating of possible combinations of the variables in policy formulation. In particular, DSM helps to visualize and analyze the best alternatives to reduce process costs, time and risk.

The case study, formulation of policy measures for a WWTP, showed the effectiveness of DSM in a domain in which such approaches have received little exploration.

The results of this study encourage further, more systematic investigation of the integration avenues of diverse modeling techniques, as well as further development of the integrative framework for WWT policy formulation. It is also our intention to develop tools to support the use of these methods with the framework.

From the fundamental research perspective, this work opens the door for further studies of theoretical aspects of the integration of system modeling methods, not just MA and
DSM, but also other methods. In future work, Business Process Modeling Notation (BPMN) could be considered as a modeling method and tool to describe more formally the integration processes underlying the proposed framework.

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Publication IV

Analysis and Ranking of Drivers for Eco-design Implementation in the Finnish Pulp and Paper Industry

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Analysis and Ranking of Drivers for Eco-design Implementation in the Finnish Pulp and Paper Industry

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Abstract

The study of eco-design practices has become an important aspect of sustainable manufacturing. Therefore, the identification and selection of key drivers for eco-design implementation is becoming essential. However, further research is needed in order to understand what are the key drivers that increase the efficiency of eco-design implementation and improve the company’s sustainability performance. The purpose of this study is to identify and evaluate the drivers for implementation of eco-design in the Finnish pulp and paper industry. The drivers are identified through literature research and a survey is conducted for their evaluation. Data analysis is performed by using ranking methodology in order to investigate and identify the key drivers for eco-design implementation practices in the Finnish pulp and paper industry. Driver for implementation “Management’s idea” and driver “Customer demand” for both continuation and implementation have the highest rank in all scenarios. In contrast, driver ‘One or few employees pushed idea’ for implementation and drivers ‘Personal quest for a better environment’ and ‘Increased employee satisfaction through environmental initiatives’ from for continuation have the lowest rank for the all scenarios. This study adds knowledge into the current literature of sustainable manufacturing and will provide insights to practitioners and decision makers in terms of eco-design implementation issues in an effective and efficient manner.

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1. Introduction

In recent years, sustainable manufacturing industry has attracted the attention of numerous researchers, both from academia and in the practitioners’ world. In the modern industry, eco-design practices have become a critical issue for most manufacturing companies. This issue is due to constantly received pressure from different stakeholders, especially government and regulatory bodies, independent environmental activists and community, non-governmental organizations (NGOs) and global competitors for the improvement of the sustainability practices.

Thus, industries and companies are forced to continuously improve their competitive advantages by creating new strategic business objectives focused on sustainable manufacturing performance indicators. For example, although life cycle assessment (LCA) is a common environmental tool used in eco-design [1], there is a lack of identifying barriers and drivers from a life-cycle perspective while highlighting the hotspots as a main basis for improvement proposals. From the eco-design perspective in the European Union (EU) policy level, some authors even argue that there is no information on the practical measures to prioritize environmental performance of product from a life cycle perspective [2].

This research is motivated by a need to identify the main drivers that increase the efficiency of eco-design implementation in the Finnish pulp and paper industry. The aim of this paper is to identify the key drivers by surveying all major pulp and paper companies in Finland, that have to be addressed to improve the efficient eco-design implementation practices, and to analyze them by ranking as perceived by industry and expert perspectives. The specific objective of this research paper folds in two perspectives.

From a fundamental research perspective, the objective is to investigate and explore the potential drivers that accelerate the improvement and efficiency for the eco-design implementation activities.

From a practical point of view, a semi-structured interview was conducted among environmental managers and decision makers and an embedded case study involving four major pulp and paper companies in Finland was analyzed through ranking methodology. The fundamental research questions are defined as follows: 1) What are the substantial initiatives (activities) driving pulp and paper companies to implement eco-design practices? 2) What are the main drivers that can accelerate the implementation of eco-design initiatives in pulp and paper industry? 3) What is the appropriate method for analysis of the efficient driving forces eco-design implementation?

To this end, the document is organized as follows. In Section 2 the relevant literature review discussing eco-design strategies, sustainable manufacturing strategies as well as the main drivers for implementation of eco-design initiatives in Finnish pulp and paper industry is presented. Section 3 provides information of the methodology, data collection and a case study chosen in the present research paper. Data analysis and results of the research paper are presented in Section 4. Section 5 conclusions and managerial implications are given followed by limitations and future work for the field of eco-design implementation.

2. Literature Review

In recent years, there have been published many research articles in analyzing and examining drivers motivating organizations to implement eco-design practices, to mention some [2], [3], [4] and [5]. For example, in [6] and [7] are identified some drivers for the adoption of sustainable manufacturing practices. In [8] are discussed the ranking of drivers for integrated lean-green manufacturing for small and medium size enterprises (SMEs) using multi-criteria decision making (MCDM).

2.1. Eco-design strategies

Eco-design practices are important aspects to reach the goals outlined in the Brundtland Report [9]. Sustainability goals can be considered design requirements such as: reduced use of energy, materials, packaging and transportation; reduction of waste and emitted pollutants, reduction of hazardous materials and substances in the manufacturing
process, improvement of waste handling protocols or techniques, recycle and reuse, utilization of greener technologies and materials, etc. to mention some [3], [5], [10], and [11].

2.2. Sustainable manufacturing strategies

Sustainable manufacturing has evolved from concept of sustainable development, which was coined in the 1980s to address the concerns about environmental impact, economic development, globalization, inequities and other factors. The link between manufacturing and its operations to the natural environment is gradually becoming attractive for the researchers and practitioners point of view. Several definition exist for sustainable manufacturing. One of the commonly referred to definitions for sustainable manufacturing is that proposed by the U.S. Department of Commerce, which describes it as “The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [12]. Today, manufacturing strategies generally account for products, processes and systems, as well as other parameters like practices, to incorporate organizational and philosophical elements. Furthermore, technological dimension is included, since manufacturing is heavily technologically driven. The technology category relating to the environment and manufacturing is affected by the following three factors: product, process and systems, and practices. Moreover, environmental manufacturing strategies based on the Malcolm Baldrige criteria are recommended for organizations by the U.S. Environmental Protection Agency (EPA), which include environmental leadership, strategic environmental quality planning, environmental quality management systems, human resources development, stakeholder emphasis, environmental measurements and environmental quality assurance [13]. Many aspects of sustainability in the context of manufacturing have been investigated, particularly in recent years. For instance, modeling and optimization challenges to sustainable manufacturing have been examined by [14], considering the product, process and systems level. Sustainable manufacturing aims to reduce environmental impacts during manufacturing activities by implementing environmental strategies such as waste minimization, resource efficiency, pollution prevention, energy efficient processes and end of life management, while considering societal and economic aspects. Progress, profitability, productivity and environmental stewardship are now seen as needing consideration by manufacturing organizations [15]. Improving environmental stewardship and sustainability, while maintaining profitability and productivity, are increasingly viewed as strategic goals of manufacturing companies.

2.3. Impact of drivers for improving sustainable manufacturing performance

In this study, the term “driver” is defined as a factor that motivates companies to adopt eco-design practices. Previous research [16], [17] has identified a comprehensive list of barriers that have influence on Finnish pulp and paper industry and slow down the process of implementation of eco-design practices. In this work, the list of drivers that has influence on pulp and paper industry to increase the level of effectiveness is analyzed. Increasing the level of effectiveness of drivers in eco-design practices is a major objective for the manufacturing industry. However, extensive literature on drivers related to implementing eco-design practices in pulp and paper industry is still missing. The increasing number of drivers for eco-design implementation can be significant; and in many countries such as Finland the trend and opportunities have been evolving [2]. Table 1 and Table 2 summarize the main drivers for eco-design practices identified from literature. In this study, the drivers are classified into either drivers for implantation or drivers for continuation. Furthermore, the drivers are sub-divided into four different categories: government, management, stakeholders and customer. In order to evaluate the answers, a Likert scale was established, ranging from 1 to 10.

Table 1. Identified drivers for eco-design efficiency implementation adopted from [4].

<table>
<thead>
<tr>
<th>ID</th>
<th>Category</th>
<th>Drivers for Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Government</td>
<td>Legislation</td>
</tr>
<tr>
<td>D2</td>
<td>Management</td>
<td>Management’s idea</td>
</tr>
<tr>
<td>D3</td>
<td></td>
<td>One or few employees pushed the idea</td>
</tr>
<tr>
<td>D4</td>
<td></td>
<td>Marketing department saw better brand image</td>
</tr>
<tr>
<td>D5</td>
<td></td>
<td>Company’s environmental profile and reputation / image</td>
</tr>
<tr>
<td>D6</td>
<td>Stakeholder</td>
<td>Pressure from stakeholders</td>
</tr>
<tr>
<td>D7</td>
<td></td>
<td>Proacticity to avoid potentially bad publicity</td>
</tr>
<tr>
<td>D8</td>
<td></td>
<td>Local community and consultants</td>
</tr>
<tr>
<td>D9</td>
<td>Customer</td>
<td>Customer’s demands</td>
</tr>
</tbody>
</table>
Table 2. Identified drivers for continuation of eco-design utilization adopted from [4].

<table>
<thead>
<tr>
<th>ID</th>
<th>Category</th>
<th>Drivers for Continuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Government</td>
<td>Environmental legislative demands</td>
</tr>
<tr>
<td>D2</td>
<td>Management</td>
<td>Company’s management quest for a better environment</td>
</tr>
<tr>
<td>D3</td>
<td>Environmental</td>
<td>Initiatives and advances in product innovation</td>
</tr>
<tr>
<td>D4</td>
<td>Stakeholder</td>
<td>The wish to be on the forefront of future legislative demands</td>
</tr>
<tr>
<td>D5</td>
<td>Stakeholder</td>
<td>Sustainable products as a competitive edge</td>
</tr>
<tr>
<td>D6</td>
<td>Stakeholder</td>
<td>Customer’s demands</td>
</tr>
<tr>
<td>D7</td>
<td>Stakeholder</td>
<td>Demands from marketing department</td>
</tr>
<tr>
<td>D8</td>
<td>Human</td>
<td>Personal quest for a better environment</td>
</tr>
<tr>
<td>D9</td>
<td>Human</td>
<td>Increased employee satisfaction through environmental initiatives</td>
</tr>
</tbody>
</table>

3. Drivers analysis and ranking methodology

The ranking methodology uses context-specific criteria sets that assess effectiveness and efficiency of driving forces (such as eco-design practices). In order to rank drivers for implementing eco-design initiatives in the Finnish pulp and paper industry, a decision support framework is developed as shown in Figure 1.

In the context of drivers in pulp and paper industry, a methodology is proposed, and later tested, to assist decision makers to consider and rank the identified drivers, to implement first. Such ranking is based on predefined criteria: time, cost, effectiveness and technical complexity.

The first step in the proposed methodology is to draw up a list of the drivers of various types (such as institutional, government, structural, political, human, cultural, stakeholders, and customer-to-customer) that are directly linked to the business’ targets: that is, identification of the drivers in an inventory from literature. Next, the criteria against which to examine the drivers are decided. After the analysts and experts evaluate the properties of each driver, they are translated into scores [ranking from 1 to 10]. This stage of inputting the basic information for each of the drivers in the inventory completes the preoperational stage. The aforementioned stage follows the standard of Multi-Criteria Decision Making (MCDM) practice in order to generate a ranking of the drivers. Moreover, the next steps in the proposed methodology provide additional and crucial information that produces robust decision-making and different results from those produced by the traditional MCDM approach. These steps are: a) Definition of the main criteria of the drivers and b) Classification and evaluation of the drivers.

3.1. Definition of the main criteria for drivers

For the ranking of the drivers, a weight was assigned to every criteria and corroborated by the experts. The percentage weight assigned to every category is: 30% for Time, 30% for Cost, 20% to Effectiveness and 20% for
Technical Complexity. Each driver was evaluated from 0 to 10 in the aforementioned categories, which are explained in detail below:

- **Time**: Represents the requirement in time needed to be invested to the particular driver, where 0 represents no time investment required and 10 represents large amount of time invested required. Rather than evaluated according to specific time periods (weeks, months, years) it is evaluated according to the perception of the evaluator.

- **Cost**: Represents the requirement in capital investment. Similar as in the case of time, 0 represents no capital investment and 10 represents large capital investment as perceived by the evaluator.

- **Effectiveness**: Represents the perceived boost of the driver in the implementation of eco-design, where 0 would be non-influential and 10 would represent essential or very highly influential as perceived by the evaluator.

- **Technical Complexity**: Intuitively, represents the level of technical difficulty associated to each driver, where 0 represents extremely simple and 10 represents extremely complex, as perceived by the evaluator. The overall weight of each driver is calculated according to the following equation:

\[
W = 0.3 \times T_V + 0.3 \times C_V + 0.2 \times E_V + 0.2 \times TC_V
\]

Where:

- \(T_V\) stands for the value assigned to the *Time* category,
- \(C_V\) represents the value assigned to the *Cost* category,
- \(E_V\) is associated to the value given to the *Effectiveness* category and
- \(TC_V\) represents the value assigned to the *Technical Complexity* category.

### 3.2. Classification and evaluation of drivers

In order to further structure and classify the identified drivers five dimensions are determined from the evaluators. This includes government, management, stakeholders, customer-to-customer and human aspects that should take into account when initiate eco-design implementation practices.

**Government dimension** - focuses on laws and regulations, the EU Directives and ISO Standards that are developed to establish both methodologies and benchmarking frameworks, e.g. Directive 2009/125/EC [18], European Council, 2006a [19] and ISO 14006:2011[20]. These drivers deal with the government and organizational policies accelerating the eco-design implementation. This growth can be related to the benefits that eco-design offers to businesses and products, some of which have been reported in the scientific literature under environmental and economic approaches [21], [22], [23].

**Management dimension** - focuses mainly at the top management commitment when resources are needed for implementation of eco-design. The level of top management commitment is therefore decisive. For instance, for purchasing, managers must decide to what extent eco-design practices affect the process and how proactive they may be with introducing sustainability. Support at board level is also crucial for creating the interest and willingness to improve the company’s sustainability performance and to establish it as a core value.

**Stakeholder’s dimension** - are with the focus on different external and internal stakeholders related to implementing eco-design. Stakeholders can be present as worker unions, environmental groups, local level government, educational and research institutions, etc. Stakeholders participate in generating a context of decision influence.

**Customer-to-customer dimension** - focuses mainly in increasing the awareness on environmental issues [6] and the performance and/or perception of the product in the market.

**Human dimensions** - focuses on understanding people, their strengths and weaknesses, their rationale and emotion as well as their desires and fears. Often represented by local communities, working personnel, etc. Stands for the social satisfaction and mood preservation of those involved or influenced by the manufacturing process.

### 4. An example application of pulp and paper industry in Finland

In this section, the proposed model is applied to a real world practical problem. The industry addressed in the case study deals with the manufacturing of pulp and paper products in Finland. The Finnish pulp and paper industry has emerged as a leader in the growing sector within the European Union and it has a good market image (reputation) at
a local and international level. The Finnish pulp and paper companies have the mission of improving the performance without compromising the environment through its business activities. Their managers are looking to accelerate the implementation of eco-design practices to achieve high score of sustainability performance. After several iterations of meetings and discussions with managers and decision makers, a detailed procedure for the identification, classification and determination of relative importance of drivers related to implementing eco-design initiatives is conducted for the case study. Further details are provided in the subsequent subsections.

4.1. Data collection

In the first step, the data was collected based on initial semi-structured interviews with design practitioners and documentation (such as annual reports, internal and external documents of the company, website content) on the Finnish pulp and paper industry. Next, the identified drivers were presented to the industry experts for their classification, categorization and evaluation. Classification of key drivers was divided into two main categories: drivers for implementation (sub-divided into government, management, stakeholders and customer), and drivers for continuation (sub-divided into government, management, stakeholder and human). The evaluation step includes the overall weight and ranking of drivers, and four scenarios were defined as average, middle, maximum and minimum. The experts evaluated all the drivers in four metrics (time, cost, effectiveness and technical complexity) during the interviews. The interviewees, a decision group of nine experts and specialists from different areas is formed, consisting of a general manager, a vice president for sustainability, a financial manager, two environmental representatives, a project manager in product safety, two manufacturing plant heads and IT specialist. Most interviews took place at the company’s facilities and few of them took place at the Lappeenranta University of Technology (LUT) premises. The semi-structured interviews took approximately 60 minutes. The interviews were conducted and recorded by the first author. All interviews were collected between January and March 2017. The participation of the interviewers was on a voluntary basis and they were selected based on their in-depth knowledge of the company’s sustainability goals and based on the unique perspective in eco-design process and practice they could provide.

4.2. Data analysis and results

Most of the drivers present a wide range of values in the expert evaluations. Therefore, in order to better represent the data, four ranking scenarios were designed. For every driver and in every category, the data was compiled as follows:

- **Scenario 1: Average** – considers the statistical general average (sum of all values over the total number of evaluations) of all evaluations for each driver in each category, followed by the weighting and ranking according to the factors assigned for each category.

- **Scenario 2: Medium Value** – represents the average in between the maximum and minimum value given in the evaluations. For example if the minimum value given is 4 and the maximum 8, the medium value is 6, regardless of the distribution of values in between. The medium value for each category is then matched to their respective weight.

- **Scenario 3: Maximum** – refers to the consideration of the maximum value given among all categories and driver evaluations regardless of the overall distribution of values. The maximum value of each category is afterwards matched with their respective weight.

- **Scenario 4: Minimum** – refers to considering the minimum value given among all evaluations for each driver and category, regardless of the overall distribution of values. Likewise, to all other scenarios, each category is matched with their weight factor for the ranking.

The concentration of results for all scenarios is presented in Table 3 for the drivers for implementation and Table 4 for the drivers for continuation.
Table 3. Analysis results from ranking drivers for implementation of eco-design in the Finnish pulp and paper industry.

<table>
<thead>
<tr>
<th>Overall Weight</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Driver 1</td>
<td>6.2</td>
</tr>
<tr>
<td>Driver 2</td>
<td>8.24</td>
</tr>
<tr>
<td>Driver 3</td>
<td>4.72</td>
</tr>
<tr>
<td>Driver 4</td>
<td>6.56</td>
</tr>
<tr>
<td>Driver 5</td>
<td>6.64</td>
</tr>
<tr>
<td>Driver 6</td>
<td>6.4</td>
</tr>
<tr>
<td>Driver 7</td>
<td>6.44</td>
</tr>
<tr>
<td>Driver 8</td>
<td>6.12</td>
</tr>
<tr>
<td>Driver 9</td>
<td>8.24</td>
</tr>
</tbody>
</table>

The total of 18 drivers (presented in Table 1 and Table 2) were independently evaluated by the experts. As it can be seen, driver 2 (Management’s idea) and driver 9 (Customer demands) from Table 3 (Drivers for implementation) and driver 6 (also Customer demands) from Table 4 (all highlighted in green) hold the highest importance ranks in all scenarios, therefore highlighted as the most influential drivers for eco-design implementation in the case study. In contrast, driver 3 from Table 3 (One or few employees pushed the idea) and drivers 8 and 9 (Personal quest for a better environment – and – Increased employee satisfaction through environmental initiatives) from Table 4 have the lowest score for all scenarios (highlighted in yellow) show the least influential drivers for eco-design implementation in the case study. Furthermore, driver 8 from Table 3 (Local public community and consultants) and driver 3 from Table 4 (Environmental initiatives advance product innovation) present the widest range of variation in ranks with a 6 and 4 rank difference respectively, meaning that the perception of the influence of these barriers varies greatly from expert to expert. Other drivers that show a relatively constant rank between scenarios are drivers 5 (Company’s environmental profile and reputation/image) and 6 (Pressure from stakeholders) from Table 3 showing relatively medium influence perception. Drivers 1 (Environmental legislative demands), 2 (Company management quest for a better environment) and 7 (Demands from marketing department) from Table 4, show a relatively high, medium and low influence perception respectively.

Table 4. Analysis results from ranking drivers for continuation of eco-design utilization in the Finnish pulp and paper industry.

<table>
<thead>
<tr>
<th>Overall Weight</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Driver 1</td>
<td>8.8</td>
</tr>
<tr>
<td>Driver 2</td>
<td>7.2</td>
</tr>
<tr>
<td>Driver 3</td>
<td>7.72</td>
</tr>
<tr>
<td>Driver 4</td>
<td>7.44</td>
</tr>
<tr>
<td>Driver 5</td>
<td>8.56</td>
</tr>
<tr>
<td>Driver 6</td>
<td>9.88</td>
</tr>
<tr>
<td>Driver 7</td>
<td>6.4</td>
</tr>
<tr>
<td>Driver 8</td>
<td>5.24</td>
</tr>
<tr>
<td>Driver 9</td>
<td>5.32</td>
</tr>
</tbody>
</table>
5. Conclusions

Implementing eco-design is an important practice is a global matter rather than national or regional, as it is essential to better formulate the anticipatory environmental strategies in manufacturing companies associated with product, processes and services, in order to enhance efficiency, as well as to minimize the environmental impact. This work proposes ranking methodology for evaluating the drivers associated with the eco-design initiatives in the Finnish pulp and paper industry. The analysis and ranking methodology is used to evaluate and rank drivers for implementing eco-design initiatives in the Finnish pulp and paper industry. The score of the drivers shown in Table 3 presents drivers 2 (Management’s idea) and 9 (Customer demand) as the highest. From Table 4 driver 6 (Customer demand) has the highest rank in all scenarios. In contrast, driver 3 (One or few employees pushed idea) from Table 3 and drivers 8 (Personal quest for a better environment) and 9 (Increased employee satisfaction through environmental initiatives) from Table 4 have the lowest rank for the all scenarios.

5.1. Research and managerial implications

This study contributes to theory and practice in the area of eco-design. First, regarding literature of drivers in eco-design in Finnish pulp and paper industry, the proposed methodology supports and integrates the existing drivers of literature. Four ranking scenarios were designed and for each driver from every category in the model, have been identified and the data has been presented. The second contribution is focused regarding of pulp and paper industry in the Finnish context. Taking into account the shortage of studies reporting the state of implementing eco-design practices in the Finnish pulp and paper industry, this paper provides a rich illustration of the driving forces for eco-design.

The results indicate that, despite of the advancement that Nordic countries have in general, and Finland in particular, it is reported that related implementation of eco-design practices there is insufficient information on the practical measures to prioritize environmental performance of pulp and paper products over their whole life cycle.

The presented research aids knowledge into the current literature of sustainable manufacturing and will provide insights to practitioners and decision makers in terms of eco-design implementation issues in an effective and efficient manner. In terms of practical contributions, the results outline actions that enable characterization of the driving forces in the proposed model, which is found based on the methodological approach chosen in this paper. Since ranking methodology approach has been adopted, in which the outcomes depend on the empirical data, the proposed and demonstrated model for analyzing the implementation of eco-design initiatives in pulp and paper industry in Finland produced results, which reflect the day-to-day business practices.

5.2. Limitations and future work

This work has certain limitations. The ranking methodology based MCDM proposed in this work consists in four main criteria and nine drivers to the implementation of eco-design initiatives. The work is focused only in the pulp and paper industry in Finland, but it can be extended with for defining and evaluating drivers in the pulp and paper industry within the European Union countries. Furthermore, it is a challenging task to identify drivers using experts and analysts inputs. The proposed ranking methodology has several weaknesses such as vagueness, uncertainty and bias. The future work will consider other decision-making methods analyze and compare the identified drivers for implementing eco-design initiatives.

Acknowledgements

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Publication V

Optimized Morphological Analysis in Decision-Making

Book Chapter In: Chechurin L., Collan M. (eds) Advances in Systematic Creativity: Creating and Managing Innovations
Through a double-blind peer review of the full paper.

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1 Introduction

Creativity has emerged as a driving force to innovation processes and systems’ design for the industry of current and future generations. Many assessment methods for innovation are already developed and can be identified in the literature. One of these methods is the Theory of Inventive Problem-Solving, also known by its Russian acronym TRIZ. Developed by Altshuller (1984), it is a remarkable instrument to boost creativity in engineering.

TRIZ focuses on the creative idea-generation process in a company’s environment (Chechurin 2016). Another promising method widely used
to support systematic creativity is morphological analysis (MA), developed by Zwicky (1969). MA is presented as a promising method for generating new concepts and finding the best solution to support decision-making. Both TRIZ and MA are well-known and commonly used methods for complex problem-solving, including techniques for idea generation and divergent thinking.

MA is a non-quantified modelling method for identifying, structuring, and studying complex problems. It is a suitable tool for addressing highly complex and ill-structured problems, also known as “wicked problems,” which are becoming increasingly frequent in a globalized world. The term wicked problems, introduced by Rittel and Webber (1973), is used to describe complex social problems that “do not have an enumerable set of potential solutions” and are multi-dimensional and non-quantifiable, with inherent technical, social, institutional, and political difficulties of addressing them (Ney 2012). Such problems are found, for instance, in strategy development, product innovation, policy design, and so on. Hence, MA is used to structure and investigate the behavior of wicked problems and discover solutions (Ritchey 2011).

Moreover, wicked problems may deal with long-term policy design, planning and complexity management, and involve many individuals and organizations with overlapping roles. Tackling wicked problems in decision-making for industrial mega-project management can happen, for example, while seeking optimization of time, cost and quality, and reduction or management of risk. This type of problem is usually formulated with many contradictory requirements, and involves many system’s elements from various functional areas. In such cases, the application of traditional multi-objective decision-making approaches has limitations. Hence, this situation allows applying a morphological approach developed by Zwicky (1969) and Ritchey (2011). Moreover, today’s industry is constantly under high pressure to generate competitive advantages and improve resource efficiency. For example, time reduction is a significant target in overall industrial project management. To address this problem, several methods and tools exist focused for optimization.

Therefore, in this chapter, we propose further improving MA by integrating it with sensitivity analysis (SA), which has never been done before. SA is an important task in multi-criteria decision-making. Moreover, SA deals with the investigation of potential changes and errors in variables and assumptions, and their impacts on the results of underlying models.
SA, applied post hoc to decision models, deals with uncertainties related to the decision outcomes and/or to the preferential judgements (i.e., value function and criterion weights). The objective is to find out how the options’ ranking changes by any modification made on the decision models (Mysiak 2010). Applying SA shows great potential for time reduction over the MA iterative part of the process.

In order to elaborate on the topic, we organize the chapter as follows: Section 2 provides background and literature review of MA and SA. Section 3 explains the proposed solution for optimization of MA through SA. Section 4 tests the theory using a numerical illustration to demonstrate the proposed method and reports results, managerial implications, and recommendations. Section 5 presents the research conclusions, limitations, and future work.

### 2 Methodological Background

This section explains the overall process of the study by providing a brief explanation of each method used. An innovative approach of applying MA complemented with SA to this problem is explored with the aim of seeking optimal solutions. Moreover, the methodological foundation of the study is based on the iterative nature of the cross-consistency assessment (CCA)—an integral part of MA—as an opportunity for further optimizing the overall process of MA. A decision tree is generated based on the morphological space and CCA is conducted in order to present the benefits of the method.

#### 2.1 Morphological Analysis

Zwicky (1969) introduced MA as a non-quantified modelling method for identifying, structuring, and studying complex problems. In principle, MA is based on the “divide and conquer” technique, which tackles a problem using two basic approaches: “analysis” and “synthesis”—the basic method for developing scientific mode (Ritchey 2018). This technique is a decomposition method that breaks down a system into subsystems with several attributes and selects the most valuable alternative (Yoon and Park 2005). In other words, MA systematically categorizes the
possible combinations of subsystems. The strength of the technique lies in its ability to provide structured models for complex problems into simpler problems, rather than offering solutions (Pidd 2009). MA can be considered as a contemporary heuristic method that has clear links with traditional approaches in different fields of problem-solving (Arciszewski 2018). It has been the subject of academic research over many years and it has been applied to a wide variety of fields and contexts such as shown in Table 1.

MA has been widely used for identifying possible variable combinations in different disciplines. It enables problem representations using a number of dimensions, which are permitted to assume the number of conditions (Eriksson and Ritchey 2002). The identified conditions in

<table>
<thead>
<tr>
<th>Application</th>
<th>References</th>
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<tbody>
<tr>
<td>Engineering and Product Design</td>
<td>Jimenez and Mavris (2010), Ostertagová et al. (2012), Ölvander et al. (2009), Sholeh et al. (2018)</td>
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<tr>
<td>Technological Forecasting/Technology Foresight</td>
<td>Yoon (2008), Feng and Fuhai (2012), Takane et al. (2009), Yoon et al. (2014)</td>
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<td>Security Safety and Design Studies Creativity, Innovation and Knowledge Management</td>
<td>Louise et al. (2009)</td>
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each dimension can be combined to derive all the possible alternatives that can solve the problem. MA requires a multidisciplinary group of five to seven experienced experts (Yoon and Park 2005), representing different aspects of the issues involved. In particular, MA provides a strong possibility for identifying unexpected combinations of new concepts. The basic procedure of the MA consists of the following stages:

- Problem definition,
- Analysis,
- Synthesis, and
- Exploration of results

Problem Definition

In this stage, the problem definition is to determine suitable problem characteristics. The individual problem-solver or a facilitated group brainstorms to define problem characteristics, also referred to as parameters. In the specific context of the study, the problem is to establish a systematic integrative approach for problem-solving, in such a way that the integrated approach supports complex problem-solving for efficient industrial management.

The specific goal is to utilize the MA and optimization of CCA through SA as modelling methods supporting decision-making in case of wicked problems, such as strategy development, product innovation, or policy design.

Analysis

After problem definition, in the analysis stage, the main task in MA is generating a morphological field, which consists of identifying and specifying the essential parameters or variables of the problem and generating the design alternatives or values for each parameter or component (i.e., a morphological class). At this stage, creative and design thinking is desirable for generating a set of potential solutions as large as possible. Finally, the morphological box (field) is created with a large solution space (see Fig. 1).
Synthesis

The synthesis stage presents the CCA proposed by Ritchey (2015). CCA involves evaluation of the feasibility of all combinations of all values and of all the variables. CCA assesses compatibility for each value via pairwise comparison (the comparison of a value from one column, or morphological class, against another value from another morphological class). The purpose of CCA matrix is to filter out infeasible configurations. The CCA is represented in a multidimensional matrix, which then is reduced to find an approximation for an optimal solution. The process is iterative in nature and time-consuming. Manual configuration evaluations in physical settings are based on a cross-consistency matrix. Therefore, optimization of the iteration process is a relevant thing to do.

Exploration

In this stage, the internally consistent combinations are synthesized, with the objective to reduce the total set of possible combinations. This step is termed assessment of consistent configurations. The CCA is computed to

![Fig. 1 A morphological matrix consisting of five parameters and their ranges of values. The matrix represents 144 (= 4 \times 2 \times 3 \times 2 \times 3) formal configurations such as (A2, B1, C2, D2, E1)]
ensure the consistency of pairwise comparisons. This step is based upon the insight that there may be numerous mutually incompatible pairs of conditions in the morphological matrix. Zwicky calls MA “totally research,” which enables in an unbiased way attempts to derive all the possible solutions of any given problem.

The main advantage of the MA method is visualization support. With the usage of CCA, MA facilitates the calculation of a large subset of consistent configurations, which is impossible to do manually. It may help to discover new relationship or configurations, which may not be so evident, or which might have been overlooked by other unstructured or less-structured methods. Importantly, it encourages the identification and investigation of boundary conditions, that is, the limits and extremes of different contexts and factors. In addition, the MA method provides various kinds of representations of the consistent configuration space. Such representations help groups to structure discussions and support decision-making.

### 2.2 Sensitivity Analysis

SA serves a wide range of applications. The SA can be applied in:

(i) Decision-making for identifying critical value/criterion, testing robustness, and riskiness of decision;
(ii) Communication for increasing credibility and confidence; and
(iii) Modelling process, for better understanding of input-output relationship and for understating the model needs and restrictions (Mysiak 2010).

SA deals with the investigation of potential changes and errors associated to the inputs and assumptions, and their impact on the results of underlying models. While the impact of uncertainties on the decision outcomes is mostly analyzed by statistical modelling and simulation, the preferential judgments are objects of uncertainty during the modelling of weights and value function (Mysiak 2010). In normal mathematical modelling and simulation, SA is used to evaluate how the changes of the variables or assumptions affect the results. When analyzing a CCA matrix, all
values contained within it (result of the evaluation and weighting of values by a panel of experts) can be considered as inputs and each of these inputs has a specific impact in the solution space (the output) generated by the evaluation of the matrix. The use of SA helps highlighting the combinations with higher impact within the solution space and of a specific value.

3 Proposed Solution

In this section, we propose and present an innovative solution using a case example. One method capable of complementing and optimizing MA is SA. According to Ferretti, Saltelli, and Tarantola (2016), SA has been applied in a very diverse range of fields, typically to calculate and estimate uncertainty of models. However, to the best of our knowledge, it has never before been applied with MA. Furthermore, the proposed use of SA aims to find the most influential combinations of the CCA matrix to reduce the time of iteration. In this study, we integrate MA with SA as a concept with high potential for time reduction.

3.1 Optimization of Morphological Analysis Through Sensitivity Analysis

MA is an approach successfully used for solving the problems where many solutions and alternatives are possible (Zwicky 1969). It consists in, first, analyzing all possible combinations of input variables, and then identifying the most promising solution. The exhaustive list of permutations of the values then forms the complete morphological space (often referred to as a Zwicky box by Ritchey (2018)). However, complications arise with this method because it is not always feasible to manually test all (or even many) of the potential solutions identified within a morphological space (Eriksson and Ritchey 2002). Therefore, Ritchey (2011) proposed the computer implementation of this method. A binary or numerical CCA matrix, generated through a panel of experts’ evaluation over the combinatory interactions of the parameters and their value pairs generates a set of solution space (Ritchey 2015). The process is iterative
in nature and it should be repeated as many times as required, to achieve a manageable solution space. A manageable solution space should have enough combinations of solutions for decision-makers to have a clear pathway, but not too many that decision-making is complex within the solution space again (Ritchey 2018). SA has been used in a multitude of fields (Ferretti et al. 2016), often aimed at testing the uncertainty levels derived of variable assumptions in mathematical models.

However, the presented approach proposes yet a different use of SA as a concept. The suggested approach proposes the use of SA to evaluate the effect of the change of each value in the matrix in the overall set of combinations of a specific value. In other words, if a pairwise value is changed from value “A” to “B” (zero to one in a binary matrix, or different numerical values in a numerical matrix), it will decrease the overall amount of combinations of value “A” in the solution space. Since every iteration of value revaluation takes time to the panel of experts, knowing which cells most affect the overall number of combinations of a certain value can save a significant amount of time for reevaluating a large CCA matrix.

4  Numerical Illustration

To test the theory, a CCA matrix with values from one to three and dimensions as shown in Fig. 2 was created in a loop of randomly generated values for one thousand iterations in MatLab, and the relative amount of combinations in each iteration is calculated according to Eq. 1:

$$RW_x^{(a,b)} = \frac{K_x^{(a,b)}}{\sum_{i=1}^{R} \sum_{j=1}^{C} K_x^{(i,j)}}$$ (1)

Equation 1 shows the method used to calculate the relative weight (RW) of an element pair, in respect to the total combinations “$K$” which are unique combinations of value “$x$,” for the position $(a, b)$ (where “$a$” is the row and “$b$” is the column in the CCA matrix) calculated as indicated by Ritchey (2010).
“R” denotes the total of rows; “C” denotes the total of columns, and “i” and “j” are the counters to calculate the total of every cell.

Figures 3 and 4 show the premise behind the CCA-plus-SA concept. The value pair P1V3 and P2V1 generates a set of 27 unique combinations of value “3” (Fig. 3), while the total unique combinations of value “3” for the row of P1V3 is 81. In contrast, the value pair P1V2 and P2V2 (Fig. 4) produces only six unique combinations of value “3.” When all value pairs are evaluated, 993 unique combinations of value “3” are produced from the entire matrix. Therefore, the cell P1V3, P2V1 hosts 2.7% of the total unique combinations of value “3,” while the cell P1V2, P2V2 generates only 0.6%. Figure 2 shows an example of the benefits of conducting SA into the CCA matrix. The picture highlights all cells with value “3” (a total of 108). Considering a scenario where it is desirable to reduce the overall amount of combinations of value “3,” the panel of experts in charge of evaluating the iteration may intuitively review only the combinations of value “3” (108 highlighted in Fig. 2, both red and yellow) saving about 56% of time required to evaluate the whole CCA matrix. Furthermore, after applying SA, it is possible, in the example case, to focus on the cells with a higher amount of overall unique combinations of value “3.” Highlighted in red are the cells of value “3” that host more than 1% of the overall unique combinations of value “3.” By reevaluating only the cells highlighted in red, it is necessary to iterate only 31
Fig. 3 Example of a large morphological decision tree for a value pair of high amount of unique combinations of value “3”
(highlighted in red) out of the 108 cells of value pairs marked with a “3.” In this manner (assuming that the revaluation of each value takes the same amount of time), it is possible to save, in the example, 71% of the time of iteration when only the cells of value “3” are evaluated, or 84% of the time of re-evaluating all the 247 values in the CCA matrix. Furthermore, by evaluating the value of only the cells highlighted in red, it is possible to reduce up to 75% of the total amount of unique combinations of value “3” from the example given.

4.1 Results

Using a multi-paradigm numerical computing software, we created a loop of one thousand iterations to generate and evaluate through SA a CCA matrix of random values from “1” to “3” and of the dimensions shown in Fig. 2. In addition, a sensitivity limit of 1% was set, meaning that every cell of the CCA matrix containing more than 1% of the total amount of combinations of a certain value is then highlighted as target for revaluation when needed. From the analysis of the results, it was found that over the loop of one thousand iterations, it is possible to reduce the iteration time an average of 63.1% when only the combinations of a certain value are evaluated, with a maximum of 88.8% and minimum of 24.7%. When compared to the evaluation of all cells in the matrix, the average time saving was 87.8% with a maximum of 96.4% and a minimum of 77.7%. Furthermore, the relative amount of combinations contained within the SA highlighted cells averaged 73.9%, while the maximum registered was 91.8% and the minimum 53.1%.
In other words, over the one thousand-loop iterations test, an average of 73.9% of the combinations of any value from “1” to “3” can be reduced by evaluating only 36.9% of the cells of the CCA matrix with a specific value, or 12.2% of all the cells of the whole CCA matrix, hence saving 63.1% and 87.8% of the time respectively. The considered timesaving assumes an equal time required to evaluate every cell in the CCA matrix. The concept of optimization of MA through SA, as presented in this section, holds a great potential for time reduction of the MA iterative part of the process.

4.2 Managerial Implications

The results of this research reveal important implications for decision-makers and managers. Several managerial suggestions are from results analysis. Decision-makers are able to define which combinations within their industrial case require more attention and which combinations will be out of the box with less significance.

The proposed approach of integrating MA with SA as a concept with high potential for time reduction can effectively and efficiently be used for managing industrial complexity. The major contribution of the research is to facilitate the decision-making process in industry. The optimization of a CCA-based model helps to facilitate decision-makers and managers to determine the relative importance of the combination sets in the CCA.

The results of the method approach could encourage managers to implement the integrated approach of MA with SA with high effect on time reduction over the iteration process. In addition, SA results help managers determine the influence of the experts’ opinion by evaluating the inputs against their impact.

4.3 Recommendations

The sensitivity limit should be chosen accordingly to the size of the CCA matrix. For a CCA matrix of, for example, 80 values, a sensitivity limit of 1% would be too low, and result in the majority of cells with the desired value being highlighted (and required to iterate), thus mostly neglecting
the advantage of SA application. Alternatively, a 1% sensitivity limit into a CCA matrix of, for example, 500 values may exclude too many cells, therefore reducing the reach of combinations reduction by applying SA. As a general rule of thumb, the authors recommend a sensitivity limit of \( (1/n) \times 2 \), where \( n \) stands for the number of cells of the CCA matrix. In the example case, \( (1/247) \times 2 = 0.8\% \sim 1\% \). SA is advised to be used in order to reduce the total amount of combinations of the desired value only for a few iterations, but not to the length of generating the final solution. After the solution space has been significantly reduced, it is recommended that the experts evaluate a slightly extended pool of solutions. This is under the reasoning that the most optimal solution is not necessarily contained within a segregated group of optimal values, but may sometimes include compromises in some combinations.

5 Conclusions and Future Work

MA is a widely used method for decision-making in planning and management, and it is often complemented with other methods to tackle its limitations. Nevertheless, the authors are unaware of research in the existing literature on optimization of MA and CCA through SA and focus on time reduction in management of complex projects.

This chapter proposed a model for optimization of MA and CCA through SA to support decision-making in project management. The integration of MA and SA, under the test conditions presented, has shown promising potential for time reduction. MA optimization was achieved by reducing iteration time. The two morphology constituents—dimensions and values—show different characteristics. The construction of dimensions requires a significant level of expert judgments compared to that of a value, since the combination of dimensions should thoroughly reflect type of interaction. To succeed in developing new innovative concepts, dimensions should be mutually exclusive and collectively exhaustive. Furthermore, the iterative process of MA and CCA receives a significant improvement using SA.

SA as an optimization tool can be performed with any set of values, in every iteration, and target any specific value (“1,” “2,” or “3” from the
example, but not limited to these). It is a powerful and adaptable tool capable of obtaining desirable solutions in a fraction of the time required otherwise. The analysis can also be automated in a spreadsheet.

In addition, the sensitivity limits can be tailored to adapt the method to CCA matrixes of any dimensions, adding another layer of flexibility. This work has some identified limitations. It is worth mentioning that the test conditions are randomly generated values and the time reduction is considering equal time requirements for evaluation of every value. Extensive application in real-world cases may show different distributions. Nevertheless, the integration of the methods should, in any case and to some extent, optimize the iteration and revaluation process with significant time reductions. Moreover, it could be argued that when focusing only on a highlighted set of cells due to their value, the possibility exists that a good or optimal solution contained within the non-highlighted cells could be missed. Nevertheless, by narrowing the combinations to iterate, a good solution (if not the optimal one) could be reached much faster, while in a complete iteration an optimal solution could still be lost among the many combinations to be reiterated. Furthermore, in order to prove or disprove this possibility, further research and application to real-life case studies is required. In a real-world situation such as that studied here, MA proved to be a successful approach for resolving complex problems and it can be applied with multidisciplinary group decision-makers. Future research can directly include integration of risk and uncertainty assessment in all modifications of MA decisions.

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A Case Study of Complex Policy Design: The Systems Engineering Approach

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Design, structure, modelling, and analysis of complex systems can significantly benefit from a systematic approach. One way to address a complex system using a systematic approach is to combine creative and analytical methods, such as general morphological analysis and design structure matrix. The aim is to propose a framework to address complex systems in two stages: first, formulation and generation of alternatives through general morphological analysis, and second, improvement and integration with design structure matrix for sequence optimization and cluster analysis. Moreover, general morphological analysis is further optimized through a novel sensitivity analysis approach reducing up to 80% the iteration time. The proposed approach is showcased in a case study of sustainable policy formulation for a wastewater treatment plant at a pulp and paper industry in Brazil. The results show that it is possible to generate a solution space that highlights the best possible combinations of the given alternatives while also providing an optimal sequence and grouping for an optimized implementation. The paper contributes to the field of conceptual modelling by offering a systematic approach to integrate sustainability.

1. Introduction

1.1. Problem Definition. In recent years, tackling problems regarding water management policies has received considerable attention. Water management has embedded within complex issues such as industrial wastewater treatment, water protection and conservation, and rational water use. The growing complexity of water management systems generates increasingly difficult policy design problems [1]. Policy design is rather complex due to the increasing amount of policy measures available for addressing the problems of a system. Consequently, policy problems are often defined as “messy” [2] or “wicked” problems [3–5]. Rittel and Webber [5] stated that “Wicked Problems do not have an enumerable set of potential solutions.” (Rittel and Weber [5] coin the term wicked problems, assigned ten characteristics to wicked problems, which have been further generalized by Conklin [4], to the following six characteristics: (1) Wicked problems cannot be understood until a solution has been developed. (2) Wicked problems have no stopping rules. (3) Solutions to wicked problems are not right or wrong they are better or worse. (4) Every wicked problem is essentially unique and novel. (5) Every solution to a wicked problem is a one-shot operation. (6) Wicked problems have no given alternative solutions.)

The term wicked problems is used to describe social complex problems that are multidimensional and possess nonquantifiable aspects, where causal modelling and simulation are not appropriate [6]. For example, in the industry sector, decision-making commonly includes complex problems associated with conflicting performance objectives and contradictory requirements, for which the application of traditional multiobjective decision-making approaches shows evident limitations [7]. In addition, there is a growing need to create a systematic approach to facilitate the definition
and structuring of relevant problems and the decision-making process among stakeholders for transparent decision support systems (DSS). A major challenge facing industrial organizations is “green policy” design and upgrading of policy measures [8]. This problem involves, for instance, knowledge management specialists, planners, and decision-makers, who all work with rather complex issues [9]. The task thus requires the creation of new tools to improve the understanding of the complexities embedded in tackling problems and reaching optimal solutions. Engineers frequently use analytical modelling methods to aid understanding the operation of complex systems, to gauge to what extent systems achieve overall their goals and targets, and how the systems in question can be improved [10].

Many traditional quantitative methods have been explored for dealing with multiobjective decision-making in the public policy realm. For example, Philips et al. [11] presented his work by applying quality function deployment (QFD) techniques to product design procedures, which are used to formulate annual policy, leading to designs that better reflect customer’s requirements. Yeomans [12] applied the coevolutionary simulation-optimization modelling-to-generate-alternatives approach in order to generate effectively multiple solutions for environmental policy formulation to municipal solid waste management. Taeihagh et al. [13] proposed a network-centric policy design approach based on network analysis and ranking of alternatives [14], often done using multicriteria decision analysis (MCDA) methods, to select and analyse the internal properties of proposed measures and their interactions in the transport policy domain.

Moreover, Taeihagh et al. [15] argued that agent-based modelling could be used for the analysis of different combinations of policy measures, aiming at generating policy packages to advance sustainable transportation. However, traditional multiobjective optimization and simulation are not sufficient to tackle complex multidimensional and non-quantifiable problems. Besides, in the case of physical sciences and economics, research in the policy domain mostly focuses on the simulation and optimization of policy alternatives, instead of their synthesis and generation. Therefore, there is still a need for further research to enhance the capacity of policy generation and evaluation of this approach. Consequently, a systematic approach is imperative, particularly when addressing complex problems, such as socio-technical systems.

The analysis of complex sociotechnical systems, like a set of policies, is a challenging problem [16]. The first reason is that the elements contained in the systems are often non-quantifiable, as they are of social, political, or cognitive nature. The second reason is that uncertainties characteristic for such complex problems are hard to be represented. The emerging need of specific tools, techniques, and systems to aid the generation, management, and enforcement of effective policies requires research on the suitability of various approaches in the context of policy instruments’ choice [17].

Various problem-structuring methods (PSMs) have been presented in the literature. Among them, general morphological analysis (GMA) [6, 18, 19] is presented as a promising method for the generation of new concepts and finding the best solution. In principle, GMA is based on the “divide and conquer technique” [20], which tackles a problem using two basic approaches: “analysis” and “synthesis”—referred to as “the basic method for developing scientific models” by Ritchey [21]. In addition, some authors propose different creative methods to be used in early conceptual design to support new concept of business model creation [22] and new concept of selection [23, 24]. GMA, as a creative method, has been used widely and tested in various domains such as policy planning and scenario development [25], strategic foresight [26], technology forecasting [27–29], and idea creation [30–32]. The core objective of GMA is to structure and investigate the behaviour and solutions among stakeholders.

From the engineering design perspective, different matrix-based tools and techniques have been developed also to aid the design process. An example of this is design structure matrix (DSM), typically used to map, visualize, and analyse the dependences and relationships among properties of a product or activities in the design process. In other words, by applying the DSM, these dependencies can be reorganized so the process can be optimized. However, no work has been done before on combining GMA with DSM. Furthermore, to the authors’ best knowledge, GMA and cross-consistency assessment- (CCA-) based optimization techniques have not yet considered optimization of the iteration process through sensitivity analysis, nor have DSM-based simulation techniques been considered for reworking of policy improvements in areas such as policy design and policy measures. Therefore, the presented research fills this specific gap in the policy design literature.

In this paper, a case study example of the Brazilian pulp and paper mill industry related to wastewater treatment plant (WWTP) is shown in order to display the empirical use of the presented model for policy formulation. Brazil is an upper middle-income country with a fast-rising economy [33], which may eventually develop into the world’s leading producer of pulp and paper. The pulp and paper industry is tackling a wide array of implementation of sustainability trends, such as (but not limited to) conservation and rational water use; development of sustainability measures for industrial wastewater treatment and water systems management becomes necessary. It is evident that there is a large potential for the adoption of sustainable practices in the pulp and paper industry in a developing country’s environment.

1.2. Motivation and Purpose of the Study. This research is motivated by an attempt to assess the potential of integrating modelling methods in such a way that the integrated approach supports complex problem solving for policy design in water management systems, while supporting sustainable development in the organization.

The aim of this paper is to develop a systematic approach for generating, designing, and improving policy alternatives using a computational methodology that integrates the diverse modelling techniques of GMA, sensitivity analysis, and DSM. The specific goal is to interlink GMA and DSM as potential problem structuring methods to tackle wicked problems and to support the decision-making of policy formulation in complex systems.
By developing a systematic approach, it is possible to (a) better understand the problem structure and to decompose it into subproblems, (b) improve analysis and optimization of the environmental policy formulation process through sensitivity analysis, and (c) decrease the time required for problem analysis and problem solving. The proposed methodology will enable decision-makers and managers to generate and explore various alternatives and to promote combination of alternatives, their optimization, and improvement of the policy development process. The proposed approach includes sensitivity analysis for optimization of the iteration process of GMA, clustering analysis through DSM, and development of the configurations of policy measures included in the policy package so that they match the objectives of the organization.

This study focuses on specific objectives as the following: the first objective is to generate policy measures or alternatives using GMA for policy design. While policy measures can be extracted from literature or derived from an expert’s opinions, different organizations can have different perceptions of policy measures to create a coherent policy. Therefore, the same policy measures may have different effects for different companies, industries, or countries. Hence, the reduced set of viable policy measures is then the subject of analysis by the stakeholders involved in policy formulation in various organizations. The second objective is to evaluate and improve the policy measures or alternatives. In light of this, a DSM approach is used for identifying the relationships of the policy measures in a qualitative manner [34].

The significance of this work, and how it differs from the other works, is that decision-makers can utilize the full potential of the proposed systematic approach to tackle wicked problems in the context of policy design and meet the company’s objective for increasing their sustainability scores.

The results are expected to further promote the use of modelling methods for policy formulation in sectors such as energy, environment, healthcare, food, water, and e-waste, in which modelling can be systematically employed as part of a DSS. Consequently, the work facilitates greater use of modelling procedures to address complex problems such as those found in environmental policy management.

1.3. Structure of the Paper. The remainder of this paper is organized as follows: first, key considerations in policy design, particularly sustainable policy design and problems of policy formulation, are briefly described. Then, the main features of the design modelling approaches used, GMA and DSM, are presented. The following section discusses the proposed approach integrating GMA, optimized through sensitivity analysis, with DSM. To illustrate the approach considered in this work, an illustrative case study is described. The findings are then revealed, and the paper concludes with the main results, discussion of contributions, limitations, and suggestions for future work.

2. Literature Review

When attempting to improve policy in areas such as water management and to mitigate problems arising from the complexity of modern sociotechnical systems, adoption of a systematic approach has become an essential part of policy design. Further consideration is given to the selection of appropriate methods, software, and tools to support understanding of the complexities embedded. For instance, Taehagh et al. [32] developed a novel framework and design support system to ease and accelerate the design of polices to meet the CO2 emission targets for the transport sector in the UK. The proposed method and computer implementation constituted the first general approach towards the development of a branch of computer-based systems that support environmental policy. Moreover, policy design research can be divided into several categories dealing with different types of objectives and criteria in public environmental policy formulation [13, 35].

In recent years, the topic of policy portfolios [36] and policy mix formulation has evolved from definition of problems via exploration of basic concepts, to development of policy measures and classification of policy measures into categories, and further to analysis of descriptive and normative scenarios. In addition, Howlett [17] defined that the nature of the criteria for effective policy design is a significant aspect in order to ensure the portfolio’s effectiveness to policy formulation and its implementation. Current research trends focus on advanced and practical levels of design policies, which involve greater integration of the related concepts and methodologies [13, 15, 35, 37]. The perception of policy design has evolved from a “single-target/single-tool” approach towards a “multitarget/multitool” approach in order to tackle complex policy design [13, 37, 38].

Earlier work on policy design and policy formulation methodology was based on dynamic modelling approaches such as network analysis [13], agent-based modelling (ABM) [39], and multiple criteria decision analysis (MCDA) [40]. Taehagh et al. [15] introduced ABM to formulation of transport policies and proposed a systematic approach for use of a virtual environment for the exploration and analysis of different configurations of policy measures. Furthermore, Wollmann and Steiner [41] proposed a model for strategic decision processes that takes into account the influence of limited rationality and organizational policy. The proposed model combines strategic decision-making, complex adaptive system (CAS), and the mathematical techniques analytic network process (ANP) and linear programming (LP) [41]. Also, complexity theory has been proposed as a complexity-driven approach to assist project management in decision-making, while defining complexity-based criteria [42].

2.1. Sustainable Policy Design. A policy is generally described using natural language, which makes it difficult to understand, especially when they occasionally compete and conflict with each other. According to Pohl [43], a “policy” is a “principle or guideline for action in a specific context” and “policy design” is “the task of selecting policy components and formulating overall policy.” Policy formulation is defined as “the development of effective and acceptable courses of action to address items on the policy agenda” [8, 44]. Policy design involves the deliberate and conscious attempt to define policy goals and connect them to instruments or tools
expected to realise those objectives, and to formulate a policy, there is a need to follow a policy agenda that meets the standards and regulations [44]. It can be considered one of the most difficult parts of the policy design process [35], and it underlies the explicit actions of policy design [8, 44]. The development of successful and acceptable policy is usually a manual task involving various activities and several teams with different objectives and criteria for policy success [32].

Within environmental management studies, environmental policies have traditionally been defined as policies that assist successful decision-making to meet the requirements of sustainable development [45, 46]. To meet the criteria of sustainable development, policies have to address the legal, technological, social, economic, and environmental aspects.

Policy formulation and policy implementation are two very different activities. Policy formulation is an important phase devoted to "generating options about what to do about a public problem" ([47], p. 29) and is inherent to most, if not all, forms of policymaking [48]. The agenda-setting step in the policy cycle focuses on identifying where to go, while the policy formulation step focuses on how to get there [49]. Considering policy formulation as "a process of identifying and addressing possible solutions to policy problems or, to put it another way, exploring the various options or alternatives available for addressing a problem," then the development or use of policy formulation tools becomes a vital part of the policy formulation process ([47], p. 30). It is difficult to conceive, or properly study, policy formulation without thinking in terms of tools. According to Dunn [50], these are tools for forecasting and exploring future problems, tools for identifying and recommending policy options, and tools for exploring problem structuring.

Some of the most traditionally used approaches are cost-benefit analysis (CBA) and MCDA in the environmental policy domain [13, 51]. However, CBA has significant drawbacks such as difficulty to measure social costs and benefits, conflict between wellbeing and financial benefits, and assigning controversial monetary value to human displacement and human life [52]. Likewise, the methods that fall under the MCDA umbrella struggle to manage decisions with inherent uncertainty, are unable to address dependencies, are prone to manipulation, and face difficulties with problem structuring [51].

Currently, decisions on what to include in policies (their synthesis) is done manually, and considering the size of the space of alternative policies, a large portion of the design space is left unexplored [32]. Moreover, Howlett and Mukherjee [53] and Chindarkar et al. [54] conducted research on comparative policy analysis, making an emphasis on effectiveness and impact of managing the policy processes [55]. Furthermore, the knowledge and objectives of the different stakeholders involved (e.g., central authority, local authority, employees, company/industry, NGOs, local residents, and researchers from academia) may differ greatly and bring dissimilar attitudes to proposed solutions, which influences the decision-making process [56].

Therefore, traditional approaches to policymaking are not well suited for solving today's complex problems. A comprehensive methodology that supports the identification, design, modelling, and evaluation of policies to tackle complex problems is still missing, and existing methodologies and frameworks to tackle the complexity of sustainable policy formulation in organizations are not fully developed. Therefore, alternative approaches and tools are required in order to overcome the limitations of traditional approaches. One possibility is to integrate multiple methods based on policy design concepts. For example, GMA and DSM are both modelling methods that may be systematically employed in a DSS [57], and this paper proposes combining GMA and DSM to facilitate modelling procedures in problem solving of complex problems such as those found in sustainable policy design.

2.2. The Complex Problem of Policy Formulation. For policy design in general, and water management in particular, decisions regarding measures for inclusion in policy require exploration of a large pool of policy options as part of the problem space [32, 53, 54]. Furthermore, designing a sustainable policy is rather complex because of the influence of different factors—technical, legal, and ethical—an example of this is management of industrial wastewaters. These factors require the adoption of a large number of different policy measures. In addition, the multiple tasks to be carried out require input from multidisciplinary teams [58]; hence, policymakers still struggle with evaluating and improving the outcome of the policy design process.

To date, a single universal approach for sustainable policy design in wastewater treatment does not exist, and suitable policy measures need to be identified based on the organization’s strategy and environmental aims. Utilization of a systematic approach to generate alternative policies by using GMA [18] and DSM [34] will help decision-makers to accelerate and improve policymaking. Furthermore, incorporating and adopting the diverse preferences from various interest groups and stakeholders will improve the policy's performance and acceptance.

While identification of feasible policy measures for complex industrial wastewater treatments can be obtained from literature review and expert inputs, it is worth noting that different companies might have different views regarding suitable policy measures. This paper considers well-defined policy measurement criteria such as legal, technical, financial, social, and environmental measures taking into consideration sustainability development goals (SDGs) [59].

The selection of policy measures to be considered is complex for several reasons. Under a simplified setting, a local company requiring an environmental permit for the installation of a WWTP would require a local permit, following regulations familiar to local experts. However, in this case study, the complexity is largely increased because it is an international company with headquarters in Finland, seeking an environmental permit for a WWTP in Brazil; thus, it requires following protocols from the company and from the location. Moreover, the specific location of the case study WWTP is next to a river separating two states, so both the regional regulation (Instituto Ambiental do Pantanal/Secretaria do Empresas y Meio Ambiente) IMAP/SEMA...
and the federal regulation (Conselho Nacional do Meio Ambiente) Conama 20 apply in this case. The selected policy measures were divided into five categories based on sustainability criteria (law-related policy measures, technical-related measures, social-related measures, and environmental measures) using expert evaluation (data collection and data analysis details are given in Sections 4.3.1 and 4.3.2). The specific policy measures identified are provided in Table 1.

2.3. GMA for Generating Alternatives. GMA was originally introduced by Zwicky [19] and Zwicky and Wilson [60] as a "non-quantified modelling method for identifying, structuring and studying complex problems." The GMA approach has been widely used for identification of possible combinations of problem variables in many different disciplines [29]. The GMA technique is a decomposition method that splits a system into subsystems with their parameters and selects the most valuable alternatives [61].

GMA enables problem representations using a group of parameters, which can take any of several values [62]. The identified conditions in each dimension can be combined to derive all the possible alternatives that can solve the problem. Yoon and Park [29] recommend a group of 5–7 experienced experts representing different aspects of the problem to be resolved. The specific way of application of GMA for this study is described further in Section 3.3.

The basic procedure of GMA is described by Wissem [63] as follows. First, in the morphological field, the system is decomposed into multiple parameters [29]. In the next step, the possible alternatives or values in each parameter are identified. The values for each parameter should be defined in a mutually exclusive manner [62]. A morphology matrix is then built with the obtained parameters and values. The whole system should be described in the morphology matrix as comprehensively as possible [23]. Finally, solutions are obtained by combining the values of each parameter. The number of possible solutions can be calculated by multiplying the number of values in each parameter [24].

GMA has been applied to a wide variety of fields and contexts like jet and rocket propulsion systems [19] and

### Table 1: List of policy measures designed for an industrial WWTP in Brazil.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementation of legislation (legal aspects)</td>
<td>Requirements in Brazilian Environmental Law, Conama 20 EU-BAT Bref (2001) sectorial Best Available Technology listing and associated limit values</td>
</tr>
<tr>
<td>Water/effluent quality (technical aspects)</td>
<td>Determination of the appropriate treated effluent quality for physical and chemical parameters</td>
</tr>
<tr>
<td>Effluent treatment plant (financial aspects)</td>
<td>Implement specific process equipment (cooling towers) to achieve legal requirements</td>
</tr>
<tr>
<td>Capacity building (social aspects)</td>
<td>Preparation and implementation of an internal program for monitoring outlet of storm water lagoons</td>
</tr>
<tr>
<td>Monitoring (environmental aspects)</td>
<td>Preparation and implementation of an integrated program for monitoring river water system of the landfill</td>
</tr>
</tbody>
</table>

computer-aided design modelling [64]. The research reported by Belaziz et al. [65] was aimed at simplifying computer-aided design model modification by integrating GMA into the design process. In addition, Ölvander et al. [66] proposed a computerized optimization framework for the morphological matrix applied to aircraft conceptual design. In the field of scenario space modelling and development, the research conducted by Coyle and McGlone [67], Coyle and Yong [68], Voros [69], and Johansen [25] confirmed that GMA has been extensively applied. Also, as reported by Haydo [70], GMA has been successfully applied to optimize complex industrial operation scenarios.

According to Ritchey [71], GMA is a "basic, conceptual (non-quantified) modelling method that can be compared with a wide range of other scientific modelling methods, including System Dynamics Modelling (SDM), Bayesian Networks (BN) and various forms of influence diagrams." Furthermore, Dyczynski [72] developed general morphological analysis for application in organizational design and transformation, while Zeiler [73] used the morphology in conceptual building design. In addition, Buzuku and Kraslawski [74] proposed applying GMA to policy formulation for wastewater treatment. In particular, GMA provides a possibility for generating unexpected combinations of policy measures [18].

The morphological approach has several advantages, including discovery of the total set of new configurations and its suitability for utilization with work groups. The use of work groups increases scientific communication and enables integration of state-of-the-art knowledge from practitioners of different fields. However, the main advantage of this method lies in its ability to structure models for complex problems in a nonquantitative manner through systematic procedures [75]. Another significant advantage is the method’s ability to provide an auditable trail [76].

Drawbacks of the method include issues with vague formulation, static analysis modelling of the values, nontreatment of variable interdependencies, and insufficient screening and selection of satisfactory combinations. Thus, the approach demonstrates limitations in defining and evaluating different parameters against each other and generating conditions within the problem space. Therefore, GMA requires support from other processes.

The most promising method in this context is DSM [34], which can describe different methods and enables visualization, analysis, and improvement of partial solutions. In this study, GMA is integrated with DSM as a screening, visualizing, and development tool [57].

2.4. DSM for Analysing and Improving Alternatives. DSM is an often-used efficient method for analysing complex systems by enabling the overview of the system and the interdependencies of the system’s elements, developed by [77, 78]. DSM provides the representation of a complex system and the dependencies, relationships, and interactions of the system’s elements [34]. In addition, DSM breaks down a complex problem into smaller problems and enables deconstruction of the organizational and functional components of a system by eliciting the relationship between components in ways that make trade-off analyses more understandable and manageable [10].

DSM generates a directed graph that describes relationships between elements or parameters for the design, management, and optimization of a complex system, organization member assignments, and activity scheduling, concentrated in an $n$ by $n$ adjacency matrix. A system of $n$ number of parameters is represented by DSM in an $n$ by $n$ matrix, in which the elements are listed in the exact same order from 1 to $n$ both in rows and in columns, where the dependencies between the parameters can be marked. When parameter $a$ depends on parameter $b$, then the cell $a,b$ (where both $a$ and $b < n$) is marked in a binary manner with any symbol, e.g., with a “•.” In case of no dependency, the cell $a,b$ is left empty [79]. When the parameters are listed in the DSM in their execution order, if cell $a,b$ is marked under the diagonal of the DSM matrix, it represents an output (or “outwards” relationship) from parameter $a$ to $b$. However, if a cell $a,b$ is marked over the diagonal of the matrix, it means that cell $a$ receives feedback from $b$ ($a$ depends on $b$).

DSM has been used in the past to solve complex decision-making problems and to improve organizational performance [77]. Therefore, DSM is considered a consolidated approach to manage complexity [9, 80–82]. DSM is known as a contemporary method that has been used for modelling and managing complex systems in engineering [83, 84], design planning [85], and operation management [86]. According to Eppinger and Browning [34], DSM can be applied to public policy because public policy and social systems are multidimensional and uncertain complex problems. Environmental policy design and its implementation is a complex problem comprising a mix of numerous types of policy instruments or measures [87, 88] adopted by a range of organizations and stakeholder participation [89].

DSM visualization provides the advantage of compactness and clear representation of essential patterns. On the other hand, as the graph becomes larger with nodes and edges, it can become difficult to understand the overall network representation. Moreover, DSM further provides the option to improve the system’s structure using matrix-based analysis techniques. Although the policy measures are listed as sequential steps in the DSM, the modelling process requires attention to their dependencies, interdependencies, and relations. The main advantage of DSM lies in combining elements/components in a novel and creative integrative framework, displaying, analysing, and improving satisfactory combinations. It is thus suitable for evaluating policy measures extracted from GMA ([90], 2015; [34]).

3. Methodology

In this section, the overall process mechanics of the two-part approach for generating and improving policy measures with experts’ evaluation feedback is described. The experts interact with the stakeholders outside the frame of this study. The methodology proposes an integrative framework for designing a sustainable policy that helps to improve policy
effectiveness, as well as a comprehensive system structure for sustainable management in organizations.

The proposed methodology is aimed at improving the impact of the different policy measures generated during policy formulation in the early stages of conceptual project design, when decision-makers start to set up and embed design solutions into problem-solving systems. During policy formulation, decision-makers and designers often model a functional net using a graph structure [91, 92], and they may produce a set of partial solutions (or alternatives) for a specific type of problem. Each set of partial solutions is interpreted and strengthened by a DSM in order to better manage the complexity and, subsequently, to aid reasoning about the sustainability of environmental policy formulation concepts.

Among alternative approaches, the choice had to be made between a matrix representation or a network representation. Network representations are often simple and easier to read; however, they are not as flexible for increasing or decreasing in size and can become almost impossible to follow if the number of inputs is very large. Ultimately, a matrix representation was chosen because a matrix can easily be rearranged, it is able to show parameters for a rather large number of inputs, it can always be expanded [93], and it can be mathematically analysed (in this case with sensitivity analysis), among other advantages.

The experts are quite familiar with the sustainability assessment of relevant environmental policy measure concepts, a very relevant factor for the evaluation of policy measures. The policy concepts themselves belong to either corporate, regional, or federal environmental regulations, and they were designed and assessed by their corresponding institutions. Moreover, the experts made it a specific goal to include or consider the most relevant policy measures that tackle the social, environmental, and technoeconomic requirements of a sustainable endeavour. Therefore, the sustainability assessment of the policy measures is not addressed in this paper.

3.1. Proposed Approach. This section examines the overall process and gives a brief explanation of each stage. The proposed new approach is divided into two stages (Figure 1):
(1) Generation: identification and derivation of policy measures with GMA, and optimization of GMA through sensitivity analysis

(2) Improvement: screening and improving the policy measures with DSM

The first stage comprises generation of sustainable policy measures or alternatives using GMA for policy design. The identification and derivation of policy measures with GMA entails the following steps: (a) identification and formulation of a library of policy measures, (b) development of a morphological matrix by building dimensions (parameters) and generating policy measures as named alternatives (values), (c) assessment of the consistency of all possible combinations of parameter values, and (d) optimization through sensitivity analysis.

The second stage consists of searching for improvements to the policy measures or alternatives using DSM clustering. Since GMA is not able to investigate and explore the dependence and interdependence relationships between policy measures or alternatives, the DSM approach is employed to analyse and better manage the policy design structure, thereby supporting the identification of the interdependencies and improving the overall process flow. The obtained results and the reduced sets of policy measures are analysed by the experts involved in policy formulation.

3.2. Problem Definition. The full complexity of water management systems and policy structure is difficult for managers and designers to understand using traditional modes of analysis. Hence, this study develops a systematic approach for exploring, generating, and improving the policy alternatives using GMA, sensitivity analysis, and DSM to identify, optimize, and improve the policy measure interactions of the system. The approach will enable managers and designers of water management systems and WWTPs to tackle the system’s complexity more wisely, a topic increasingly relevant in developing regions like China and Brazil [94, 95].

The environmental policies, provided in Table 1, are virtually represented in the GMA matrix so that it is possible to analyse their effectiveness in the specific project. The main target of the resulting designed policies is the improvement of the quality of measures and their performance. In an optimal scenario, all stakeholders are involved.

3.3. First Stage: Generation of Policy Measures with GMA. The first stage of GMA comprises the identification and formulation of a set of specific policy measures related to the problem, in the illustrative case in this work, an industrial WWTP. The policy measures identified were categorized by experts into economic, environmental, social, and technical sustainability criteria, using the GMA tool to build the morphological box during the workshop.

There are multiple ways to conduct GMA. Zec and Matthes [96] elaborated in four possible ways the application of the method: (1) alone, (2) in a relaxed manner with like-minded individuals, (3) in a workshop with experts and stakeholders, and (4) in a distributed manner through remote online workshops. The third option, a workshop with experts and stakeholders further detailed by [97], is the approach chosen for this study. The exercise for evaluation of policy measures and classification into the categories they belong was performed with preprinted forms, white paper, and pen from a groupthink of experts in a workshop, described in Section 4.3.1.

The identification and derivation of policy measures with GMA comprise the following steps: (a) identification and formulation of a library of policy measures and classification by the experts, (b) development of a morphological matrix by building dimensions (parameters) and generating policy measures as named alternatives (values), (c) assessment of the consistency of all possible combinations of parameter values, and (d) optimization through sensitivity analysis for subsequent iterations.

The experience and knowledge of experts from a wide range of disciplines is required to develop the morphological matrix. A methodology to gather and organize this knowledge through a participatory dialogue process, such as a structured workshop, is also required. Approaches like CCA, invented by Ritchey [18], allow the number of alternatives and iterations to be reduced significantly. The reduced set is then the subject of process analysis by the experts involved in the policy formulation. The role of expert opinion and experts’ participation in decision-making is crucial for environmental policy management [98].

The set of combinations of alternatives obtained from the morphological matrix is analysed, screened, and improved with DSM. The consistency of combinations is evaluated by exploring all possible combinations of the morphology matrix via CCA. The sensitivity analysis step proposed in this work can further optimize the CCA process and highlight the most relevant parameters.

3.4. Second Stage: Improvement of Policy Measures with DSM. The use of DSM enables visualization of the dependencies and interdependencies of combinations of variables and values. Once optimal combinations of policy measures have been derived using GMA (described in detail in Section 4.1.3), it is necessary to integrate them into the DSM for screening and improvement of the policy measures and to select the most suitable set of policy measures for implementation. More specifically, the proposed approach (shown in Figure 1) can be used to observe the complex interactions and improve the understanding of underlying relationships between the policy measures. To perform the analysis of the policy correlations, this study suggests visualizing and identifying of the best alternatives for implementation, and reorganizing and improving the process flow of policy measures with DSM. Since results extracted from GMA are used as input to DSM, the DSM process can be applied from the analysis step.

4. Illustrative Case Example

The proposed approach is illustrated with a case study for the construction, operation, and maintenance of a large industrial WWTP. This case study was conducted with an
international engineering and consultant firm, hereafter, called "company A." Due to increasing pressure for sustainable wastewater treatment globally, particularly in the pulp and paper industry [95], there is a significant need to design and formulate sustainable policies that promise sustainable solutions for wastewater treatment facilities. The new plant was planned to become an integrated facility in the wastewater sector through collaboration with the local community, potential stakeholders, and enhanced engagement with the company in the region. Industrial water systems management, including wastewater treatment systems, is a complex problem that requires expert’s knowledge and years of experience in a wide range of disciplines. The decision-making can be classified as a complex problem, the activity is situated on a federal river forming a border area between the states of Mato Grosso do Sul and Sao Paulo, Brazil, and there are large capital and operational costs involved, as well as involvements of multistakeholders. A relevant factor in the development of sustainability measures for industrial wastewater treatment is the participation of stakeholders from various levels and functional areas of society [99] involved in the process.

Some policy measures are of interest to both internal and external stakeholders. This interest generates a “policy measure-stakeholder” relationship. In the case in progress, stakeholders are

(i) Central Authority. The central authority commonly is responsible of taking care for the issues that could destabilise the relationships between the present stakeholders and any other possible conflict on stage.

(ii) Local Authority. The local authorities have interest in the issues related to the legal aspects of operation of the plant on their territory.

(iii) Employees. The main interest of the employees is in environmental aspects, health and safety (EHS) issues including training programs, and workshops aiming for the better quality of the working conditions.

(iv) Company/Industry. For the company or industry, and more specifically its top management level authority, the key interests are the health and safety conditions for the staff, aiming for the high quality of the work environment and other social aspects that are directly linked to the plant operation and its maintenance, and of course to profit from the activity.

(v) NGOs. The civil society and NGOs have interest in the topics that are related to broader perspectives, which target environmental, advocacy, and other social issues, e.g., human work rights.

(vi) Local Residents. Local residents and the community around usually have interest in the public services provided by WWTP, and having impact on their healthy lifestyle.

(vii) Researchers from Academia. The researchers from the academia typically have high interests in providing conditions for collecting data and sampling analysis for scientific research purposes.

The stakeholders provide feedback to the experts. Afterwards, with the acquired knowledge, the experts participated in the workshop. In this way, stakeholders remotely influence the decision-making in this case study. Nor were the experts or the stakeholders previously familiar with the methods used for this research.

4.1. Identification and Derivation of Policy Measures with GMA. The empirical knowledge of experts, stakeholders, and members of society is required to compile available environmental measures [99]. The compiled set of environmental policy measures has been generated as described in Section 2.2, and the selection is depicted in Section 3. Measures may be regulatory (e.g., legislation on emission limits), economic (e.g., taxation of wastewater discharge), technical (e.g., investment in best available technology), social (e.g., increase in social awareness), and environmental (e.g., decrease in pollutant concentrations in effluents). The measures can be quantitative or qualitative and affect all aspects of sustainability. The policy measures can be ranked by effectiveness, time of deployment, cost, risk, uncertainty, technical complexity, social acceptability, and organizational complexity, depending on whether the policy is meant to adapt or mitigate, or whether it is designed to reward improvements or punish noncompliance.

4.1.1. Development of the Morphological Matrix with Design Parameters or Dimensions and Alternatives or Values. After problem definition, the main task in GMA is generation of a morphological field comprising the most relevant dimensions (parameters) and production of design alternatives (values) for each parameter. Therefore, policy measures must be identified and formulated in accordance with sustainability criteria to achieve the environmental targets. These sustainability criteria are considered the constituents of the WWTP and can be used as the morphological field’s parameters. The parameters of the morphological field are set in the header in the spreadsheet table, and their generated values are placed under each parameter. Figure 2 shows the development of a morphological field with five parameters—legal, financial, technical, social, and environmental dimensions—and their values. The specific WWTP parameters in the case study are written in bold. For each parameter, possible values are defined in their respective column.

Table 2 illustrates the combination of different design parameters and values obtained using the principles proposed by Zwick [19] and Ritchey [18], and Table 1 shows the list of policy measures designed for the industrial WWTP in Brazil considered in the case study. The combination of policy measures of one partial solution from every column leads to the overall principle solution or policy formulation concept. Since GMA has many iterative steps [100], modifications in the morphological matrix can occur throughout the process [82]; thus, the proposed GMA optimization
through sensitivity analysis described in Section 5.2 is thus justified.

The GMA approach outlined in this study may take practitioners and researchers up to several weeks to execute. The actual time and effort required for any GMA application depends on several factors, including familiarity with the process being modelled and the degree of difficulty of information gathering and defining and evaluating parameters and values. In the case of parameter building, Geum and Park [30] and Geum et al. [101] suggest that an expert-based qualitative approach provides more powerful results. Although some GMA models can be extracted automatically from project management models, most entail the direct involvement of experts.

4.1.2. Assessment of Consistent Combinations of All Parameter Values. CCA, proposed by Ritchey [18], can be used to evaluate all the feasible combinations of parameter values. CCA assesses compatibility for each value via pairwise comparison (one pairwise value from one column or morphological class with another pairwise value from another morphological class). To reduce the problem space, decision elements are compared pairwise by experts (further detailed in Section 4.3.1) in terms of their control criteria. Each condition is compared with another condition and evaluated for internal consistency, which is noted as their assigned values in a matrix called the CCA matrix.

Figure 3 presents the CCA matrix for this study. The assessment of the conditions, done by the experts, is carried out by evaluating the level of compatibility of two parameters during a workshop described in Section 4.3.1. For example, the question is asked to the experts: is $P_1$, $V_4$ - Parana River

<table>
<thead>
<tr>
<th>Table 2: Combinations of parameters/values.</th>
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<tbody>
<tr>
<td>Parameters</td>
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<tr>
<td>Values</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>V1</td>
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<tr>
<td>V2</td>
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<tr>
<td>V3</td>
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<tr>
<td>V4</td>
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<tr>
<td>V5</td>
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<tr>
<td>V6</td>
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</tbody>
</table>

Figure 2: Development of the morphological field with five parameters and their values. BAT: Best Available Technology; IFC EHS: International Finance Corporation Environmental Health and Safety; COD: chemical oxygen demand; ADt: air dry tons; AOX: absorbable halogen compounds; DO: dissolved oxygen concentration; NTU: nephelometric turbidity unit; ECF: elemental chlorine free; Conama: Conselho Nacional do Meio Ambiente.
water quality requirements (Class II) compatible, neutral, or incompatible with $P_3$, $V_1$ “Cooling towers”? When compatible, the interaction is evaluated as optimal (marked with a 3 in the CCA matrix). When neutral, the interaction is evaluated as acceptable (marked with 2). Finally, if the interaction is incompatible, it is evaluated as nonacceptable (marked with a 1). The values assigned in the example shown in Figure 3 are 122 (49.4% of the total) optimal combinations, 27 (11%) acceptable, and 98 (39.6%) nonacceptable.

The CCA matrix reduces the total problem space to an internally consistent solution space. Furthermore, the CCA in a multidimensional matrix is then reduced to find an approximation for an optimal solution. A "parameter-block" is the two-dimensional block of cross-referenced values between two parameters and their values, and it is shown as alternate white and shaded blocks in Figure 3. In some cases, all the cells in the blocks will have optimal combinations, meaning that these two blocks do not constrain each other. If more than half of the block contains optimal values, the solution space will not reduce significantly. On the other hand, if more than half of the values are nonacceptable (or even fewer if distributed in large consecutive arrays), then it will risk choking the model, and no solution will be possible. Poorly and nonadequately defined parameters make the process difficult to manage, and parameters and values must be reformulated in such cases. This process can prove rather time-consuming, and consequently, it is very important to optimize the iteration. This work proposes the use of sensitivity analysis to address this issue.

Figure 3: Cross-consistency assessment matrix.
4.1.3. Generation of New Sets of Policy Concepts. As seen in Figure 3, some parameter values have more optimal combinations than others do. The parameters with the highest amount of optimal combinations share between each other nineteen satisfactory sets of policy concepts. These identified parameters are grouped into three clusters or packages as a final result of GMA. The mentioned clusters are the following.

The parameter value \( P_1 \), \( V_1 \) “requirements in Brazilian environmental law, Conama 20,” seen in the first row of Figure 3, has eleven optimal pairwise combinations with other values. The parameter values \( P_{2V1}, P_{2V4}, P_{3V1}, P_{3V3}, P_{4V2}, P_{4V3}, P_{5V1}, P_{5V3}, P_{5V4}, P_{5V6}, \) and \( P_{5V6} \), described in detail in Table 3, optimally combine pairwise with \( P_1, V_1 \). For simplicity purposes, \( P_1, V_1 \) and its optimal combinations will be referred from this point onwards as policy 1. The high level of compatibility of policy 1 makes it relevant for further analysis and is selected for further analysis in the next stages.

Likewise, the parameter value \( P_1, V_3 \) “World Bank/IFC EHS Guidelines” (third row in Figure 3) combines optimally pairwise with twelve parameter values. The parameters combining in an optimal manner with \( P_1, V_3 \) are \( P_{2V1}, P_{2V2}, P_{2V3}, P_{3V1}, P_{3V2}, P_{3V3}, P_{4V1}, P_{4V2}, P_{4V3}, P_{5V2}, P_{5V3}, and P_{5V6}, \) and from now on will be referred to as policy 2. Just as in the case of policy 1, the high compatibility of this cluster makes it relevant for further analysis and thus is selected to be taken to the next stages.

In the same manner, the parameter value \( P_1, V_4 \) “Parana River Water Quality Requirements (Class II)” (fourth row of Figure 3) combines optimally pairwise with twelve parameter values. The parameter values mentioned are \( P_{2V3}, P_{2V4}, P_{2V5}, P_{3V4}, P_{3V5}, P_{4V2}, P_{4V3}, P_{5V1}, P_{5V3}, P_{5V4}, P_{5V5}, and P_{5V6} \) and henceforth constitute policy 3. Just like in the previous two cases, the high compatibility of policy 3 is enough to be taken for further analysis in the following steps.

A list of the parameter values and the amount of optimal pairwise combinations is shown in Figure 4, where policies 1, 2, and 3 are highlighted in yellow.

After defining and identifying the packages or clusters (policies 1, 2, and 3), these clusters are presented back to the experts for their judgment and approval according to their experience. Figures 5 and 6 show the selection of the parameter values that generate optimal combinations of policies 1, 2, and 3 for new WWTP according to environmental experts’ judgments. All the parameter values that present optimal combinations to either/or policies 1, 2, and 3 are highlighted in yellow.

To facilitate visualization of the correlation between the policies and their optimal parameter values, a colour code was created and assigned to each policy, further improving understanding of the interactions of the parameter values contained within policies 1, 2, and 3. Red, blue, and green were assigned to the parameter values that combine optimally with policies 1, 2, and 3, respectively. When policies 1 and 2 share a common optimal parameter value combination, it is marked as magenta. Similarly, when policies 2 and 3 share optimal parameter values, it is marked as cyan, and for policies 1 and 3, yellow is used. When policies 1, 2, and 3 share a common parameter value, it is marked as purple.

Figure 6 shows the constitution of the policy packages and the parameter values they have in common. For example, policy package 1 is constituted by 11 parameter values, all of which appear common to either or both policy packages 2 and 3 as indicated in Figure 6. Likewise, it can be seen also for policy packages 2 and 3.

4.2. Optimization through Sensitivity Analysis. In order to establish a relationship between parameters to evaluate

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**Table 3**: Detailed description of the parameters that combine optimally pairwise in policy 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>P2V1</td>
<td>Determination of the appropriate treated effluent quality for physical and chemical parameters</td>
<td></td>
</tr>
<tr>
<td>P2V4</td>
<td>Determination of dissolved oxygen and turbidity in the river water</td>
<td></td>
</tr>
<tr>
<td>P3V1</td>
<td>Implement specific process equipment (cooling towers) to achieve legal requirements</td>
<td></td>
</tr>
<tr>
<td>P3V5</td>
<td>Storm water management by sectorial storage lagoons</td>
<td></td>
</tr>
<tr>
<td>P4V2</td>
<td>Environmental training events for workers of production departments</td>
<td></td>
</tr>
<tr>
<td>P4V3</td>
<td>Detailed training of operators of effluent treatment plant concerning process, incomes and outcomes, and equipment and their control and maintenance</td>
<td></td>
</tr>
<tr>
<td>P5V1</td>
<td>Preparation and implementation of an integrated program for monitoring river water</td>
<td></td>
</tr>
<tr>
<td>P5V3</td>
<td>Preparation and implementation of an integrated program for monitoring treated effluent</td>
<td></td>
</tr>
<tr>
<td>P5V4</td>
<td>Preparation and implementation of an integrated program for monitoring groundwater at the production area</td>
<td></td>
</tr>
<tr>
<td>P5V5</td>
<td>Preparation and implementation of an integrated program for monitoring groundwater as a part of monitoring system of the landfill</td>
<td></td>
</tr>
<tr>
<td>P5V6</td>
<td>Preparation and implementation of an internal program for monitoring outlet of storm water lagoons</td>
<td></td>
</tr>
</tbody>
</table>
the compatibility of different combinations, meetings and workshops must be organized with experts and iterations must be repeatedly executed to achieve a desirable solution. A desirable solution requires that the number of optimal combinations is big enough to provide options for the decision-makers to analyse, but not so big that the decision-making within the optimal solutions becomes complex again. According to [102], there are no strictly defined higher or lower limits to how extensive the share of optimal combinations from the total possible combinations should be, as it is very case-specific. Nevertheless, the share of optimal combinations typically lies between 1% and 10% of total possible combinations.

However, gathering the required experts for the amount of time required to go through several iterations may be a difficult starting point for the project. In order to optimize the iteration process, a sensitivity analysis can be executed across the CCA matrix (Figure 3) to reduce the number of relationships to evaluate, thus reducing the time required for evaluative iteration.

Figure 7 shows the proportional distribution for pairwise combinations of the values shown in Figure 3. The ratio of combinations of Figure 7 is calculated by obtaining the amount of combinations of value exclusivity and in each cell (containing a parameter value) of the CCA matrix, then aggregating them row-wise. Value exclusivity in this case

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means that cells of value 3 are combined exclusively with other cells of value 3 in the matrix. While in theory the method can combine parameters of all values, an optimal solution in principle (and for this case) is considered to be constituted by a combination of optimal parameter values.

For the CCA matrix presented in Figure 3, the optimal combinations of parameter values of the cell P1, V3–P2, V1 presented in Figure 8(a) and P1, V4–P2, V3 in Figure 8(c). Simultaneously, the aforementioned cells have more optimal correlations than, for example, P1, V4–P2, V1. Based on this premise, by analysing the CCA matrix (Figure 3), it is possible to extract the number of correlations of every combination pair (cell) and then compare the number of correlations to the total number of combinations of a selected value, which is done taking into account each parameter value (optimal, acceptable, or nonacceptable) separately.

All cells in a row are then aggregated according to their parameter value, as shown in Figure 7. For example, the row P1V1 adds up to 286 unique combinations when only cells of the same value are combined, out of which 226 are of optimal value, 30 are acceptable, and 30 are nonacceptable (or 79.2% optimal, 10.4% acceptable, and 10.4% nonacceptable).

Figure 7 also shows the total distribution of optimal, acceptable, and nonacceptable combinations (right-hand column). The high number of optimal combinations (49.1%) means further iterations can be considered to reevaluate the combinations if considered necessary, in order to reduce the number of optimal combinations. The proposed sensitivity analysis is aimed at identifying the effect of modifying the dependence value between two specific elements in the total number of solutions. As expected, some combinations are strongly correlated to more parameters than others.

Figure 8 shows all the unique optimal combinations (value 3) present for the cells: (a) P1V1–P2V1 (20 combinations), (b) P1V3–P2V1 (27 combinations), and (c) P1V4–P2V3 (20 combinations). The rows containing these cells (P1, V1, P1V3, and P1, V4, respectively) contain the largest number of optimal correlations, both in relative numbers (columns 1, 3, and 4 of Figure 7) and in absolute numbers. Therefore, these rows, and the elements contained within them, are thus selected to be the policy packages policy 1, policy 2, and policy 3, chosen for analysis in DSM. The large number of optimal combinations present in these specific cells highlights the potential impact of modifying the values in such cells whilst, for example, changing the value of cell P1V5–P2V5 could only reduce 4 optimal combinations from the solution space.

Figure 8 shows also something that is not so clear at first glance. For every additional parameter block, the amount of combinations increases in an exponential manner, at a ratio proportional to the number of parameter values of that parameter block. Likewise, the larger number of parameter values within a parameter block would increase significantly the amount of combinations. For example, if an additional parameter block of the size of P4 (the smallest parameter block from the example as visible in Figure 2) is added, the total possible amount of combinations would triple. This can potentially become rather problematic, as the evaluation time and computational time can eventually increment beyond the capabilities of a workshop. Hence, decreasing the amount of parameter pairs to be evaluated becomes paramount, opening a gap for sensitivity analysis to select only the most influential values to evaluate, based on their relative weight, thus decreasing dramatically the array of evaluations to be made by experts in one iteration.

Equation 1 shows the method used to calculate the relative weight (RW). The RW of an element pair in respect to the total combinations "K" (subsequent combinations calculated as indicated by Ritchey [18] and exemplified in Figure 8) of value "x" (1, 2, or 3 in the example) in position (a, b) (where "a" is the row and "b" is the column of the CCA matrix). In the equation, "R" stands for the total number of rows; "C" stands for the total number of columns. For example, if the number of combinations of value "3" of the element pair (3,4) is seven (K(3,4) = 7) and the total of subsequent combinations of all element pairs is one thousand, then the RW of (3,4) would be 0.7%.

\[
RW_a^{(i,j)} = \frac{K_a^{(i,j)}}{\sum_{i=1}^{C} \sum_{j=1}^{C} K_a^{(i,j)}}
\]

Figure 9 shows the relative weight of all element pairs, colour-coded to facilitate the evaluation; the colour coding and sensitivity limits assigned for this case are also shown.

Once the RW of all element pairs has been analysed and classified, it is possible to focus on reiteration of the combinations with higher RW value. By reevaluating only the combinations with higher RW, shown in red and yellow in Figure 9, up to 54.4% of the total combinations can be shifted from one value to another. This means reducing the optimal solution space by reevaluating and possibly changing a combination value from optimal to acceptable, for example, while reiterating only 45 out of the 247 element pairs that
Figure 7: Percentage of optimal, acceptable, and non-acceptable pairwise combinations of parameter values.

Figure 8: Example of unique optimal combinations for the cells associated with policies 1, 2, and 3 (a, b, and c, respectively).
would otherwise be reiterated. Assuming that experts would require roughly the same amount of time to evaluate every combination, conducting a sensitivity analysis in the iteration presented reduced the iteration evaluation time by 81.8% in this example. To put it into numbers, the evaluation of 247 combinations was done in this case during a two-day workshop described in general by Ritchey [97] and in detail for the case study in Section 4.3.1. Considering 9 hours of work (9 hours of the second long day of the workshop) to evaluate 247 combinations, the time required breaks down into an average of one hour and forty minutes.

Moreover, through a 1000 loop of randomly generated values achieved in all iteration experiments carried out with a matrix of the same dimensions (done in Matlab R 2014), the whole iteration process would take approximately one hour and forty minutes.

If only 45 element pairs are evaluated instead (as in the example), the whole iteration process would take approximately one hour and forty minutes.

Using the same method, a reduction of over 80% was achieved in all iteration experiments carried out with different variants of the values obtained from the case study. Moreover, through a 1000 loop of randomly generated values for a matrix of the same dimensions (done in Matlab R 2014), it was found that by revaluating an average of 12.2% of total cells, the solution space can be reduced by an average of 73.9%. Even considering that the revaluation of certain cells, the solution space can be reduced by an average of 81.8% in this example. The above mentioned participants selected and evaluated 25 policy measures for the WWTP during the workshop. The first author was personally involved in the workshop as a facilitator and direct observer and responsible for data collecting. The interviews and the workshop were not recorded due to confidentiality, but detailed notes of answers and their feedback were taken from each interview and the workshop. The members of the multidisciplinary group validated the policy measures for further procedures of the DSM model.

4.3.1. Data Collection. The data gathering was conducted through a workshop preceded by interviews and feedback with design practitioners at the industry. In the case under study, a two-day workshop was organized with the participation of 10 experts. Among them were designers and engineers, planners, and managers of different backgrounds and specializations, to rate the sets of policy measures and derive suggestions for reorganization and improvements. Their opinions serve as the directional driver for policy design improvements towards sustainability. The formed group of experts consisted of one general manager, one financial manager, one environmental manager, two heads of manufacturing plants, two designers, two senior planning analysts, and one IT manager with more than 10 years’ experience. None of the workshop participants had any experience with GMA or CCA. One of the advantages of carrying out the evaluations of the pairwise combinations in a group of 10 experts is that the individual bias factor is greatly mitigated, as the ultimate chosen value is the result of a consensus between all 10 experts.

The workshop held had a duration of two full days in March 2016 at the facilities of the engineering and consulting company. The experts in the workshop participated on a voluntary basis. A meeting face-face with the experts for a detailed interview preceded the workshop. The abovementioned participants selected and evaluated 25 policy measures for the WWTP during the workshop. The first author was personally involved in the workshop as a facilitator and direct observer and responsible for data collecting. The interviews and the workshop were not recorded due to confidentiality, but detailed notes of answers and their feedback were taken from each interview and the workshop. The members of the multidisciplinary group validated the policy measures for further procedures of the DSM model.

4.3.2. Data Analysis. When building a DSM model, the main objectives are to highlight the information in the system’s elements, to design parameters or elements that can be represented in a DSM graph, and to identify the intensity of...
dependencies among those elements. A dataset involving policies 1, 2, and 3 with their 19 attributes obtained from GMA (see Figures 4 and 6) was used to build the elements of the DSM matrix. The data was used to examine options for chunking components into subsystems. The analysis was conducted for each dimension of dependency and for the overall DSM.

First, the policies and their elements or policy measures were mapped on a 25×25 square DSM (that includes all policy measure of the system for consistency), where these policy measures are listed vertically in the "Component" column. Second, the dependencies of the elements to be analysed are defined. Based on the dependencies, a DSM graph structure was built and analysed using the ProjectDSM v2.0 (http://www.projectdsm.com) software, which provides an automated DSM optimization step for triangulation. By running the software, the input data is analysed using an algorithm for optimization that consists of two steps: sequencing and clustering. The sequencing step rearranges the order of the parameters to improve the flow based on their dependencies, while the clustering step groups the elements that are strongly interconnected.

The total interactions for each of the 19 elements were assessed, resulting in 22 entries (red dots in Figure 10) in the dataset. The screening mechanism was conducted and implemented using the ProjectDSMv2.0 project planning software. This is extremely helpful for users to optimize the policy sequence within coupled blocks. Therefore, analysing and optimizing the interactions and sequence of policy measures can significantly improve the performance of the policy formulation process [90].

4.3.3. Model Analysis and Visualization of the Policy Measures for Implementation. The policy measures obtained from GMA are listed in the DSM as rows and columns symmetrically. All policy measures’ dependencies used for the DSM were obtained during the first day of the workshop for the identified policy measures. The corresponding interaction levels are identified and evaluated in joint collaboration with the experts, chosen, based on their familiarity with the system.

The DSM results are formulated through clustering and partitioning, which, in turn, are used for future work on development of business process diagrams. The second stage of the proposed approach consists of visualization and analysis of the optimal clustering alternatives in order to estimate and reduce the process costs’ required time and evaluate risk (high, medium, and low) and effort (days). The visual representation of the policy measures’ dependencies provides further insight into the relationships within a complex system, sometimes highlighting information that otherwise could have been missed. This type of evaluation is a fundamental characteristic of design-science research.

The improved sequence of policy in the DSM is shown in Figure 10, indicating the elements and their interdependencies after clustering of the original matrix. This DSM analysis resulted in four clusters, each of which was then defined as a development sequence of policies. The four coupled blocks (in sequence) are (1, 2, 3, 4, 5, 6, 7), (9, 10), (13, 14, 15, 16, 17), and (18, 19, 20). Each block is visualized separately and independently, and this places the most connected elements in the matrix. It can clearly be seen that four shaded blocks along the diagonal were defined based on interdependencies that generally require reorganizing policies with stakeholders.

From the elements’ interactions shown in Figure 10, the elements in the lower part of the matrix require inputs from the elements of the upper part of the matrix. Because of this, the elements in the upper part of the matrix should be given higher priority, in order to improve the flow of the policy by executing first the elements that are input to others.
4.3.4. Reorganization and Improvement of the Process Flow of Policy Measures in DSM. The last stage consists of the reorganization, screening, and improvement of policy process flow understanding via DSM sequence optimization. In the proposed framework, different interaction types in DSM clustering (given in Figure 10) document the original structure of the policy design system in the case study. Next, the DSM partitioning function reveals the most interdependent elements in the matrix. Last, the policy design structure is reorganized and optimized by splitting the larger interdependent clusters into smaller subgroups (shown in Figure 11) that are more manageable.

Although various criteria have been proposed to evaluate policy measures and packages [37, 103], details for a policy package have rarely been revealed with DSM. In this study, interdependent elements were identified and analyzed for improvements in the presence of domain specialists and experts involved in the project, who found the process and its resulting sequence of policy measures quite valuable.

The reorganized structure of the DSM matrix through partitioning in Figure 11 proposes an improved organizational structure for the policy measures in the system, thus minimizing the instances of rework. For instance, Figure 11 shows that the element in row 2 "Implement cooling tower" is related to the element "Requirements in Brazilian Environmental Law, Conama 20" under subsystem "Implement legislation," which makes perfect sense. This element in row 2 "Implement cooling tower" originally belonged to the effluent treatment plant (financial aspects in GMA matrix).

As a result, managers and designers should consider to restructure their policy design system by reassigning row 2 to "Implement legislation," for better coordination. Through several computational clustering iterations, optimal solutions are reached while considering internal and external block dependencies under certain assumptions. The results were approved by the panel of environmental experts, engineers, and managers who participated in the workshop.

5. Discussion and Managerial Implications

5.1. Policy Measure Development vs. Policy Formulation. GMA and DSM were conducted with the participation of a panel of domain experts in a two-day workshop that resulted in a policy measure reduction model. The concept of policy measures is very complex, since the policies are generally described using natural language, making them difficult to be interpreted, especially when they are competing and conflicting with each other. Another important characteristic of policy measures is that they are intangible, and due to this, it is very hard to systematically break down, analyze, and improve. This is especially difficult considering integration of the sustainability aspects in the early stage of conceptual design. Hence, DSM allows the mentioned analysis and improvement.

5.2. Development of Parameters and Development of Values in GMA. The two morphology constituents, parameters and values, are very different in nature. The definition of parameters requires comparatively more consideration of an expert in comparison to a value, because the interaction of parameters should comprehensively represent the policy concept. To achieve the development of innovative solutions of policy concepts, parameters must be mutually exclusive and collectively exhaustive. Furthermore, the iterative process of GMA and CCA receives a significant improvement through the use of sensitivity analysis [104]. Sensitivity analysis as an optimization tool can be performed with any set of values, in every iteration, and target any type of combination (optimal, acceptable, and nonacceptable). It is a powerful and adaptable tool capable of obtaining desirable solutions in a fraction of the time required otherwise. The analysis can also be automated in a spreadsheet. In addition, the sensitivity limits can be tailored to adapt the method to CCA matrices of any dimensions, adding another layer of flexibility.
5.3. Defining Information Flow, Dependencies, and Interdependencies in DSM. The most important constituents of DSM—system elements, defining the strength of these element dependencies and interdependencies, and cluster analysis—set the foundation for the advantages of DSM usage. The approach itself helps to illustrate the power of the process architecture, provides a clustering and reorganizing method, and shows all possible information hidden in the policy design and its measures or alternatives. A key insight from the model is the difference between planned and unplanned iterations. With this tool, it is possible to increase the overall understanding of environmental sustainability policy design of wastewater treatment system management among different experts and decision-makers.

5.4. Involvement of Field Experts. The proposed approach of combining GMA and DSM can effectively and efficiently be used for managing complexity of environmental policy formulation. Both GMA and DSM approaches are qualitative methods, and the involvement of the expert’s judgment has high impact in the evaluation of solutions, elimination of contradictions in the GMA, building of the elements, and analysis and evaluation of DSM dependencies. In addition, close collaboration between academic or research institutions and companies could facilitate the work of domain experts in order to make optimal decisions.

5.5. Managerial and Practical Implications. The current manuscript has multiple implications for policy design science and society. The main contribution is facilitation of the decision-making process for decision-makers and industry experts. It allows designers and managers to become aware of the complexity of policy measures’ generation, policy improvement, and policy implementation in a DSS context. Once the basic understanding of these policy measures and issues is acquired, the relevant authorities have further insights for addressing and tackling counterproductive measures implemented in the industry. The authorities also become more capable of recognizing the most important policy measures in order to coordinate efforts to create effective strategies. This work finally aids decision-makers to prepare and practice the implementation of DSS. The proposed approach may assist decision-makers to identify and assess the environmental policy measures, while enabling them to enhance the sustainability of the companies implementing the measures.

The results show the potential of applying DSM to significantly improve the development of policy alternatives, accelerate the design of policies, and improve the entire system’s policy structure towards sustainable management. The findings obtained in this work are aimed at further promoting the use of modelling methods in policy formulation with the purpose of performance and effectiveness improvement of policies.

In this sense, the proposed approach targets to support decision-making and to address specific problems in a systematic manner.

6. Conclusions

Environmental policy formulation is a rather complex process that is affected by several uncertain factors, non-quantifiable problems, and unspecified targets. In this paper, a new systematic integrative approach to environmental policy formulation based on structural modelling techniques was presented. The goal of the proposed approach is to support the design of policy, management, and planning in the early stages of conceptual design. The aim was to integrate GMA and DSM, using a case study for generation and improvement of policy measures. The approach consisted of two stages:

1. First stage: generation, identification, and derivation of policy measures with GMA
2. Second stage: improvement and screening of the policy measures with DSM

Furthermore, GMA optimization was achieved by reducing iteration time using sensitivity analysis. The methodology for combination of GMA with DSM and avenues for their integration was discussed in detail.

The effectiveness of this integrated approach was illustrated with a real case study of industrial WWTP management planning. The results show the potential of applying GMA and DSM to significantly generate and improve the development of policy alternatives, hasten the design of policies, and improve the whole system’s policy structure for sustainable management in WWTP for pulp and paper companies.

The main results of this paper are as follows:

(i) The integration of DSM with GMA improves the overall process from conception and design to integration for improvement and management of complex systems
(ii) The combination of DSM with GMA significantly reduces the policy design process time
(iii) GMA optimization using sensitivity analysis reduces the iteration time
(iv) Combined GMA and DSM methods can define absolute priority importance in a DSS

6.1. Contributions

6.1.1. Theoretical Contribution. This study has several contributions to the field of the sustainable policy design literature. First, from the fundamental research perspective, this work opens the door for further studies of theoretical aspects of the integration of system modelling methods beyond GMA and DSM. Second, from a methodological point of view, this work expands to the utilization in policy formulation area, by applying systematic modelling methods to sustainable policy design. The presented approach contributes to and promotes research in the domain of multicriteria analysis.
and multiobjective optimization using the complex and challenging example of industrial water systems management. Third, the proposed optimization method of CCA through sensitivity analysis is showcased.

6.1.2. Empirical Contribution. From the practical perspective, the suggested approach will help decision-makers and managers in dividing a complex problem into subproblems in the process of policy design. Using creative and analytical modeling methods and decision tools can further improve environmental decision-making performance of policy formulation. Finally this study is, to the authors’ best knowledge, the first attempt to develop a systematic integrative approach for environmental policy formulation. Therefore, the suggested approach may be used for future policy design in the current and potentially other fields.

6.2. Limitations. Along with these contributions, however, there are some limitations. First, the GMA-based structural model was not an easy task to implement by the participants in the workshop. All participants needed several iterations of the exercise and guidelines from the facilitator on how to develop the parameters and generate the values in order to familiarize them with the methods. The proposed approach, particularly development of parameters and values in morphological space, is rather significant and strongly dependent on the expert’s judgment. Second, the suggested optimization of GMA and CCA through sensitivity analysis should be tailored by the user to matrices of varied dimensions, as well as decide specific sensitivity limits for each case. Since a large number of combinations are generated in a solution space, appropriate optimization methods and tools can be considered and procedures should be prepared to facilitate the process.

Third, the DSM visualization and clustering method is required to validate the relationships of the policy measures. However, it is still unclear how to prioritize the implementation of policy measures within the clusters. Currently, the scope of this study is limited to the sustainable policy design for water management system and WWTP. Further research and application of the proposed approach to other contexts is still required and will be addressed in future work.

Data Availability
The data used to support the findings of this study have not been made available because of privacy agreements with the interviewees and their respective companies. However, the form used to gather information from the interviewees is available and attached in Appendices A, B, and C.

Additional Points
Highlights. (i) Proposes an integrated framework for generation and improvement of policy measures. (ii) Shows the benefits of combining general morphological analysis and design structure matrix. (iii) Proposes optimization of general morphological analysis through sensitivity analysis. (iv) Presents a case study to show strengths and weaknesses of methods in policy design.

Conflicts of Interest
The authors declare that there is no conflict of interests regarding the publication of this paper.

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Supplementary Materials
Appendix A: the list of questions used in the first day of the workshop for building the MA matrix. Appendix B: a blank morphological matrix used to build and analyse the parameters and values in GMA in the first day of the workshop with participation of stakeholders. Appendix C: cross-consistency assessment (CCA) matrix used in the second day of the workshop with experts for assessment of parameters and their values. (Supplementary Materials)

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