Jyri Hanski

SUPPORTING STRATEGIC ASSET MANAGEMENT IN COMPLEX AND UNCERTAIN DECISION CONTEXTS

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 863

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Abstract

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Supporting strategic asset management in complex and uncertain decision contexts

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Strategic asset management can be defined as strategic-level coordinated activity of an organization to realize value from assets. Strategic asset management decisions are often uncertain and complex. Uncertainty refers to the state of deficiency of information related to an event, its consequences, or its likelihood. Complex systems have a history, are evolving and involve large numbers of interacting elements, where minor changes may have major consequences. The complexity and uncertainty of strategic asset management stems from factors such as long lifetimes of assets, imperfect information on which the decisions are based, multiple stakeholders with possibly conflicting needs and requirements, various system hierarchical levels, complex technologies, information systems and organizational structures, and varying asset types and life cycles. In addition, strategic asset management is influenced by many emerging trends and perspectives such as regulation and legislation, sustainability, circular economy and climate change, enabling technologies, ecosystem, business models, risk management, robustness and flexibility, and life cycle information management. To manage the uncertainty and complexity related to strategic asset management, there is a need for methods supporting strategic asset management in complex and uncertain decision contexts.

The main research question of this dissertation is "how to manage assets in complex and uncertain decision contexts with strategic decision support methods". To answer this question, the research provides a holistic view of the emerging trends and perspectives affecting strategic asset management. Furthermore, existing methods are identified and classified, and novel methods are developed and tested for supporting strategic asset management under complex and uncertain decision contexts. The key concepts related to asset management, emerging trends and perspectives, and existing decision support methods are explored. Three novel methods are developed and tested using design science research as a research strategy. Qualitative data collection and analysis methods are utilized.

The main contributions of this dissertation are: 1) a novel classification of emerging trends and perspectives in strategic asset management 2) advancing the classification of methods supporting strategic asset management in complex and uncertain decision contexts, and 3) developing and testing novel methods for supporting asset management decisions in complex and uncertain decision contexts.

Keywords: Strategic asset management, uncertainty, complexity, decision support, decision context, method, design science research

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To my family and friends, for all your support, and laughs, over the years, thank you.

And, finally, to my fiancée Elli and son Viljami – thank you for your love and support.

Jyri Hanski
October 2019
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List of Abbreviations

AM = Asset Management
BF = Business Finland
CBA = Cost Benefit Analysis
CC = Climate Change
CE = Circular Economy
CRINE = Cost Reduction in a New Era
DDI = Digital Disruption of Industry
DSR = Design Science Research
EC = European Commission
EU = European Union
IAM = Institute of Asset Management
IJSEAM = International Journal on Strategic Engineering Asset Management
ISO = International Organization for Standardization
JUFO = Finnish Publication Forum rating for journal/conference
LCCA = Life Cycle Cost Assessment
MCDA = Multi-Criteria Decision Analysis
OEM = Original Equipment Manufacturer
P = Publication
RDM = Robust Decision-Making
SAM = Strategic Asset Management
SRVM = Strategic Robustness Visualization Method
Tekes = Finnish Funding Agency for Technology and Innovation, nowadays Business Finland
TCO = Total Cost of Ownership
ToPDAd = Tool-Supported Policy Development for Regional Adaptation
WCEAM = World Congress on Engineering Asset Management

Contents

Abstract

Acknowledgements

List of Abbreviations

Contents

List of Publications

1. Introduction 13
   1.1 Research gap and motivation 15
   1.2 Scope of the study and research questions 17
   1.3 Research process 19
   1.4 Outline of the original publications 20
2. Theoretical background 23
   2.1 Strategic asset management concept 23
   2.2 Perspectives and emerging trends in strategic asset management 28
      2.2.1 Strategic asset management: external view 29
      2.2.2 Strategic asset management: internal view 34
   2.3 Decision support methods for strategic asset management 38
      2.3.1 Classification of decision support methods 39
      2.3.2 Methods for supporting strategic asset management in complex and uncertain decision contexts 40
3. Methodology 45
   3.1 Research philosophy 45
   3.2 Research approach 47
   3.3 Research design 48
   3.4 Research strategy: design science research 49
   3.5 Data collection and analysis 52
   3.6 Quality of the research and limitations 54
4. Summary of publications 57
   4.1 Publication 1: Strategic asset information management: experiences from Finnish companies 57
   4.2 Publication 2: Sustainability in strategic asset management frameworks: A systematic literature review 59

4.3 Publication 3: Circular economy models – opportunities and threats for asset management 60
4.4 Publication 4: Methods for value assessment of water and sewer pipelines 61
4.5 Publication 5: A method for visualization of uncertainty and robustness in complex long-term decisions 63
4.6 Publication 6: Assessing climate change adaptation strategies – case of drought and heatwave in the French nuclear sector 66
4.7 Overview of results 68
5. Discussion and conclusions 71
5.1 Managing assets in complex and uncertain decision contexts 71
5.2 Theoretical contributions 79
5.3 Managerial implications 81
5.4 Suggestions for further research 82
References 85

List of Publications

(1): Hanski, J., Jännes, J., Valkokari, P., & Ojanen, V. (2016). Strategic asset information management: Experiences from Finnish companies. In: Koskinen, K. T., Kortelainen, H., Aaltonen, J., Uusitalo, T., Komonen, K., Mathew, J., & Laitinen, J. (Eds.), Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015). Lecture Notes in Mechanical Engineering, pp. 227–236. doi: 10.1007/978-3-319-27064-7_22.

The author was responsible for designing the research and writing the paper. The co-authors provided valuable comments that improved the paper. The paper was accepted based on a peer review of the full text.

(2): Hanski, J. & Ojanen, V. (2019). Sustainability in strategic asset management frameworks: A systematic literature review. Manuscript accepted to be published in International Journal of Strategic Engineering Asset Management (IJSEAM).

The author was responsible for the design, conducting the analyses and writing the paper. The co-author provided valuable comments that improved the paper.

(3): Hanski, J., Valkokari, P., Kortelainen, H., & Ahonen, T. (2017). Circular economy models – opportunities and threats for asset management. Proceedings of Maintenance Performance Measurement and Management Conference (MPMM2016) 28 November 2016 in Luleå, Sweden. pp. 81-86. ISBN: 978-91-7583-841-0.

The research was jointly designed by the authors. The author was responsible for the writing. The co-authors were involved in the evaluation of the circular economy models from the perspective of asset management. The author took primary responsibility for revising the paper during the peer review process. The paper was accepted based on a peer review of the full text.

(4): Hanski, J., Luomanen, T., Kortelainen, H., & Välisalo, T. (2013). Methods for value assessment of water and sewer pipelines. International Journal of Strategic Engineering Asset Management, Volume 1, Issue 4. doi: 10.1504/IJSEAM.2013.060470

The author was primarily responsible for designing and writing the paper. The review for water and sewage sector assessment indicators, technologies and methods was jointly written. The author took primary responsibility for revising the paper during the peer review process. The paper was accepted based on a double blind review of the full paper.

(5): Hanski, J. & Rosqvist, T. (2017). A method for visualisation of uncertainty and robustness in complex long-term decisions. In Risk, Reliability and Safety: Innovating Theory and Practice - Proceedings of the 26th European Safety and Reliability Conference, ESREL 2016. doi: 10.1201/9781315374987-445.

The author was primarily responsible for writing the paper. The research was jointly designed. The co-author is responsible for the formalization of the mathematical foundations of the method. The paper was accepted based on a peer review of the full text.

(6): Hanski, J., Rosqvist, T., & Crawford-Brown, D. (2018). Assessing climate change adaptation strategies – case of drought and heatwave in the French nuclear sector. Regional Environmental Change, Volume 18, Issue 6, pp. 1801-1813. https://doi.org/10.1007/s10113-018-1312-z.

The author was primarily responsible for writing the paper. The paper was jointly designed. The co-authors provided the data for the case study based on the requirements set by the author. The author took primary responsibility for revising the paper during the review process. The paper was accepted based on a double blind review of the full paper.

1. Introduction

Supplying high quality potable water and removal of wastewater, provision of electricity and energy, processing of fuel, food and goods and related logistics chains are integral parts of a healthy modern society. In the delivery of these services, a diverse range of tangible and intangible assets are needed. These functions are supported by planning, designing, manufacturing or constructing, installing, operating, maintaining, modernizing, dismantling, disposal and re-using materials, components and systems. The goal of asset management (AM) is to execute these processes as efficiently and effectively as possible while securing the availability, reliability and sustainability goals set by the owners, employees, regulation, legislation and all other relevant stakeholders. All things considered, AM plays a crucial role in the efforts to secure the main supportive functions of modern society.

ISO 55000-2 (2014) provides a general definition of AM that is applicable to all types of assets, such as financial, physical and non-physical, infrastructure, or human assets: “the coordinated activity of an organization to realize value from assets.” AM has the potential to bring many benefits to organizations adapting its principles. Benefits of AM include improved financial performance over the short and long-term, informed asset investment decision-making, better risk management, enhanced services and outputs, enhanced customer satisfaction, improved governance, demonstrated social responsibility and compliance, enhanced reputation, improved organizational sustainability, and improved efficiency and effectiveness (IPWEA, 2006; ISO 55000-2, 2014). AM provides management principles and perspectives on the planning and execution of maintenance tasks for all types of organizations, including energy providers and highway agencies (Schraven, Hartmann and Dewulf, 2011; Volker et al., 2014). It also provides asset knowledge, such as life cycle costs of alternative investment proposals, for management and decision support activities (Hastings, 2010; Povey and Peach, 2013). Through AM, asset managers gain more time to consider their options and select the most viable decision alternatives (Povey and Peach, 2013). AM also supports maximizing asset value and minimizing the risks involved (Moon et al., 2009), and meeting regulatory requirements (Younis and Knight, 2014). Furthermore, it highlights a holistic system perspective of assets, not just a view of discrete activities, such as maintenance (Too, 2012; El-Akruti, Dwight and Zhang, 2013).

AM consists of a set of strategies, methods, procedures and tools. Alternatively, it can also be considered as a philosophy such as condition-based, performance-based, service-based or service level driven or risk-based asset management (Marlow et al., 2007). AM can also be seen as an umbrella subject encompassing a range of management activities carried out by asset-intensive companies (Mehairjan, 2016). It optimizes asset value through activities such as planning, investment financing, engineering, operations, maintenance, refurbishment and replacement (Komonen, Kortelainen and Räikkonen, 2006, 2012; Lutchman, 2006). Expectations for AM vary. Some industries require single viewpoints and techniques, whereas some require comprehensive and integrated evaluation, development and optimization techniques (Komonen, Kortelainen and Räikkonen, 2006).

AM has similarities with the maintenance concept. EN 50126-1 (2017) defines maintenance as the “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.” In fact, according to asset managers in the Netherlands, AM is regarded as the professionalization of maintenance management (Wijnia and Herder, 2010). The key difference is that AM covers the full life cycle of an asset, instead of only the operation phase, although the maintenance community has taken steps towards a more holistic view of the life cycle (Waeyenbergh and Pintelon, 2002; Wijnia, 2016).

AM activities such as operation, maintenance and replacement have been practiced from the moment the first assets were installed. One of the early systematic and documented approaches to AM was first developed in the 1960s, when US military policy planning related to its nuclear arsenal was analyzed to determine the most efficient budget allocation (Mehairjan, 2016). The idea of applying AM to asset-intensive industries originates from financial AM (Brown, 2010). At the time, the term "asset management" was also used for the first time in the title of a scientific paper, although the first papers focused on financial assets. Management of physical assets (terotechnology) was referred to in a scientific publication for the first time in 1975. The definition of terotechnology is very close to the current definition of AM, with an industrial focus. (Wijnia, 2016).

Several elements of AM have their origins in practice. Public infrastructure was the focus of the Australian and New Zealand professional community from the 1980s onwards, and of the North Sea oil and gas industry in the 1980s and early 1990s (Woodhouse, 2003; Wijnia, 2016).

Quantitative risk management approaches were first developed in heavily regulated industries (petroleum refining and chemical processing), whereas manufacturing industries focused on optimizing process uptime and system availability (Mehairjan, 2016). The North Sea oil industry included risk thinking into AM following the Piper Alpha offshore incident and the Cullen Report (Cullen, 1990; Woodhouse, 2014). Additionally, decreasing oil prices and the resulting financial challenges sparked the CRINE (Cost Reduction in a New Era) initiative, which focused on extending the life cycles of ageing assets and reducing capital requirements (Wijnia, 2016).

In the late 80s and early 90s, the deregulation of utilities, transport and public services sparked a transition in organizations' view of infrastructure assets: they were no longer seen a cost center but instead as a profit center that contributes to earnings growth (Too, 2012). Organizations were encouraged to adopt a holistic approach to manage their assets, and AM was consequently discovered by the newly privatized UK utility sector, which founded the Institute of Asset Management (IAM) in 1994 (Too, 2012; Wijnia, 2016).

AM can be considered a relatively new and contemporary discipline in comparison to related disciplines such as construction, facilities, maintenance, project management, economics and finance. In addition, contributions to the AM body of literature are mainly made by government organizations and industry practitioners in the form of standards, guidelines and reports (Too, 2012). The IAM was involved in the creation of the first AM standard PAS 55 (IAM, 2004) and its second edition (IAM, 2008) (Mehairjan, 2016; Wijnia, 2016). The most recent AM standard is the international AM standard (ISO 55000-2, 2014), which is built on the basis of PAS 55. Other recent developments in the AM community include organization of the first annual World Congress on Engineering Asset Management (WCEAM) in 2006 and the establishment of the International Journal on Strategic Engineering Asset Management (IJSEAM) in 2012. However, the number of scientific publications on strategic asset management (SAM) and AM in general remains limited.

In recent decades, technological advancements related to sensors and actuators, information systems, analytics, artificial intelligence and robotics, among others, have increased the potential for the availability, reliability and transparency of assets and asset-based information. These advancements have enabled new types of services and network structures to emerge and support AM in organizations. The availability of data on the use, location and condition of assets over their life cycle has increased drastically. Current disruptive digital trends are expected to change asset-intensive industries similarly to the changes that have already taken place in the media and banking industries (e.g. OECD, 2015). In addition, information management has emerged over the years as an integral part of AM.

Concurrently, sustainability and greenness have gained some interest in the AM community (e.g. Liyanage, 2007; Marlow, Beale and Burn, 2010; ISO 55000-2, 2014). Assets and AM are identified as crucial factors in reaching climate change (CC) mitigation targets, reducing pollution and other environmental damages and moving towards sustainability (Hanski and Valkokari, 2018). Circular economy (CE) is presented as a solution to sustainability and resource sufficiency issues (Geissdoerfer et al., 2017). The aims of AM and CE are largely aligned (Hanski and Valkokari, 2018) and AM should have a major role in the transition towards pervasive CE practices.

1.1 Research gap and motivation

As a testament of the emerging nature of the field, some criticism has been posed regarding the status of AM as a scientific discipline and as an approach that is beneficial to organizations. The challenges of scientifically soundly demonstrating the benefits of AM are reflected in the lack of publications in this field (Hodkiewicz, 2015). In addition, due to its governmental and industrial basis and the moderate advancement of the field, AM literature lacks well-grounded theories (Too, 2012). More in-depth knowledge and analysis is needed regarding the factors affecting SAM and the methods and tools used for supporting SAM decisions.

The focus of this study is on the strategic-level decisions that affect the future development trajectories of an organization. Although strategic management and decision-making have been widely studied, the strategic aspects of AM have received less attention (Komonen, Kortelainen and Räikkönen, 2012). The need to integrate strategic management and AM is recognized in the literature (Younis and Knight, 2014). In addition, some dimensions of AM decisions have been based more on intuition and visions rather than structured and well-tooled analyses (Komonen, Kortelainen and Räikkönen, 2012). Typically, AM decision support, such as maturity models, is focused on the technical and operational levels and neglects the important strategy, policy, social and governance perspectives (Laue et al., 2014).

There is a lack of a holistic perspective among SAM methods (Komonen, Kortelainen and Räikkonen, 2006; Mahmood et al., 2015). Extreme events and risk management are only limitedly considered in SAM (Komljenovic et al., 2016). To manage the uncertainty and complexity related to SAM, there is a need for holistic frameworks and methods that consider emerging trends and perspectives such as sustainability, CC and digitalization. In the context of this dissertation, framework is defined as a concept which aims to provide an overall picture, distinctions and/or to organize ideas. Additionally, there is a need for an overview of the perspectives and trends affecting SAM that complements the earlier research on SAM (e.g. Komonen, Kortelainen and Räikkonen, 2006; Liyanage, 2012; Brown et al., 2014; Mahmood et al., 2015). A classification of perspectives and trends would help organizations to select a suitable decision support method. The methods presented in this dissertation consider perspectives and trends that are usually not covered in AM frameworks, such as sustainability, CE and CC requirements. Existing research on sustainability seldom considers AM perspectives, and AM lacks guidance on considering sustainability aspects (Niekamp et al., 2015). Similarly, CE is generally not focused on AM perspectives and requirements. In addition, AM has paid only limited attention to CE and there is a lack of methods to support AM decisions from the perspective of CE (Korse et al., 2016). CC adaptation is not considered in AM maturity models (Mahmood et al., 2015).

AM decisions at the strategic level are often uncertain and complex. Uncertainty stems from, for instance, the long lifetime of assets and imperfect information on which AM decisions are based. Many internal and external factors increase the complexity of AM and uncertainty of the operating environment, such as: sustainability, interaction between built assets and the natural environment, resilience, life cycle management, community demands, information management, new types of governance arrangements, changes in demand, the competitive environment, economic obsolescence, security of economy, climate change, compliance with requirements, technological development, acquisitions, changing operating practices and requirements, wear and aging, and technical and environmental obsolescence (e.g. Hastings, 2010; Komonen, Kortelainen and Räikkönen, 2012; Liyanage, 2012; Brown et al., 2014). SAM-related decisions involve multiple stakeholders with possibly conflicting needs and requirements (Liyanage, 2012). SAM decisions concern various system hierarchical levels including, for instance, component, sub-system, system, and production system levels (Kunttu et al., 2016; Hanski and Valkokari, 2018). SAM decisions involve complex technologies, information systems and organizational structures. Further complexity originates from the varying asset types and life cycles, for example from single-use assets to water and sewage pipes that can, under the right conditions, last for hundreds of years. All of these factors increase the complexity and uncertainty of SAM decisions.

There are some methods that could be used for tackling complex and uncertain decision contexts in SAM, including risk assessment (Kramer and Peppelman, 2012; van der Lei, Wijnia and Herder, 2012; Sun, Ma and Mathew, 2013; Attwater et al., 2014), portfolio management (Kramer and Peppelman, 2012), real options and serious gaming (van der Lei, Wijnia and Herder, 2012), multi-criteria decision analysis methods (MCDA) (MacGillivray et al., 2007; MacGillivray and Pollard, 2008; Parida, 2012; Volker et al., 2014) and scenario methods (Hall et al., 2004; Nielsen, Chattopadhyay and Raman, 2013). In complex and uncertain decision contexts the use of traditional methods alone, such as input from technical experts, strategic planners or managers, may be insufficient (Rzevski and Skobelev, 2014; Komljenovic et al., 2016). Therefore, there is a need for novel methods and applications based on the existing methods for supporting SAM under complex and uncertain decision contexts. The identified decision support methods only limitedly consider how perspectives such as CC adaptation and mitigation, robustness, flexibility, stakeholder needs, CE, sustainability, and life cycle and asset information management affect SAM decisions. Therefore, novel applications that consider these emerging trends and perspectives are needed. The individual methods presented in this dissertation have novelty also in themselves. As an example, in CC mitigation and adaptation there is a need for methods that consider uncertain futures, deep uncertainty, scenarios and robustness (Lempert et al., 2006; Whateley, Steinschneider and Brown, 2014; Maier et al., 2016).

There are some classification frameworks for methods supporting SAM (e.g. AWWARF, 2001; Herder and Wijnia, 2012). These frameworks aim at supporting the selection of decision support methods for certain decision contexts. However, there is a need for classification frameworks that consider uncertain and complex decision contexts and other crucial factors. In addition, decision support methods from the risk management and strategic management fields should be included in the framework as they could also support SAM.

In summary, there is a need for a more holistic view of the emerging trends and perspectives related to SAM and for advancing the classification of methods supporting SAM. In addition, novel methods are required to better consider the emerging trends and perspective in SAM.

1.2 Scope of the study and research questions

The scope of this dissertation is built around asset management, decision support methods for complex and uncertain decision contexts, and strategic management and the relationship between them.

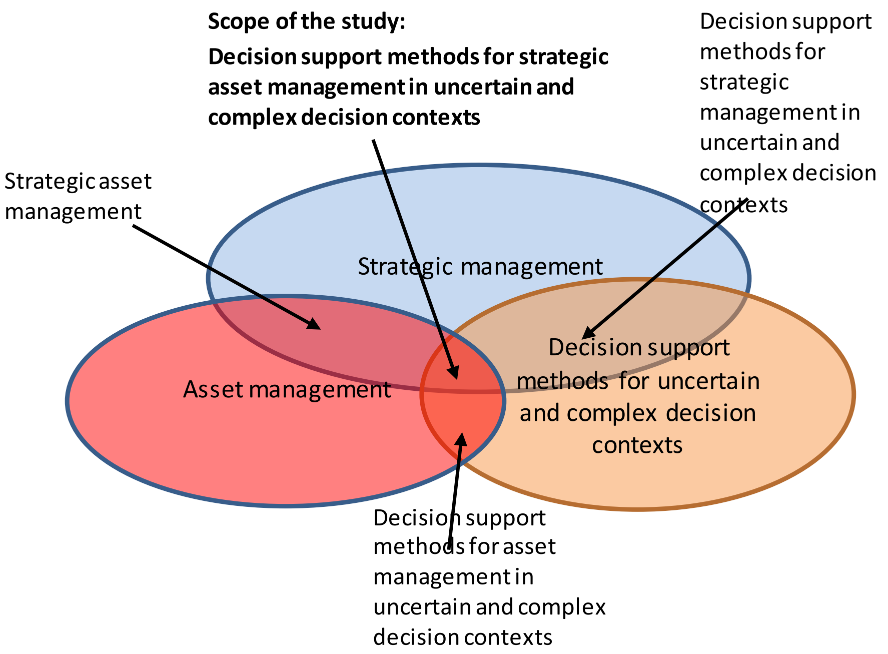


Figure 1. Scope of the study.

The main objective of this dissertation is to support SAM-related decision-making, and the aim is to make SAM decision-making more holistic by considering emergent trends and perspectives and to utilize decision support methods that are valid for the identified decision context. The dissertation addresses identified research gaps by increasing the understanding of SAM in complex and uncertain decision contexts. Emergent trends and perspectives in SAM are introduced, and existing and novel decision support methods that consider these trends and perspectives are elaborated. Additionally, a categorization of decision support methods for SAM is presented.

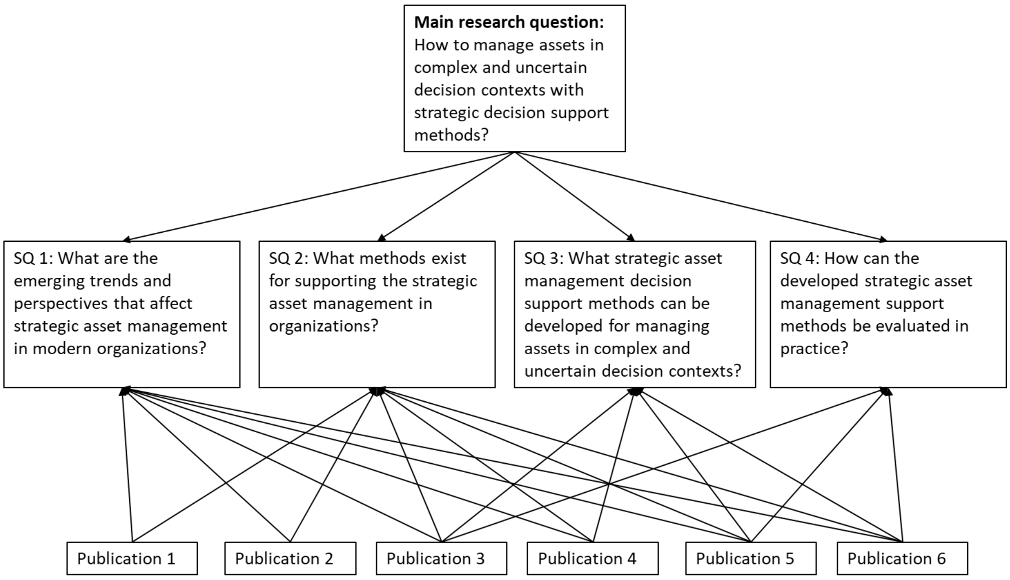


Figure 2. Main research question, subquestions and publications in this dissertation.

The main research question is: "How to manage assets in complex and uncertain decision contexts with strategic decision support methods?" This dissertation focuses on strategic decisions and mainly the planning aspect of asset management. To answer this question, four subquestions (SQ) were formulated.

The first subquestion, "What are the emerging trends and perspectives that affect strategic asset management in modern organizations?", aims to present the background and state of the art of SAM. It focuses on the emerging factors that decision support methods for SAM should consider. It is based on the observation that methods supporting SAM do not sufficiently cover all important perspectives and emerging trends. Firstly, SAM and its related terms and concepts are introduced. Secondly, key trends and perspectives and their impact on SAM are discussed. Thirdly, a holistic framework for emerging SAM-related trends and perspectives is constructed. This subquestion supports the main research question by introducing key terms and concepts and emerging trends and perspectives that SAM should consider.

The second subquestion "What methods exist for supporting the strategic asset management in organizations?" focuses on the characteristics of existing methods for supporting SAM. It introduces the methods that are used in SAM and found in the decision support literature. A systematic literature review is utilized to deepen the understanding of the methods available. As a result, a framework for classification of decision support methods in complex and uncertain decision contexts is provided. This subquestion supports the main research questions by introducing the existing key methods for supporting SAM in complex and uncertain decision contexts.

The focus of the third subquestion “What strategic asset management decision support methods can be developed for managing assets in complex and uncertain decision contexts?” is on the development of novel methods for managing assets in complex and uncertain decision contexts. These methods help to fill the existing research gap of developing methods and applying existing methods to new application areas and considering emerging trends and perspectives that have previously been considered only to a limited extent. The methods are developed for sectors such as water and sewage, electricity infrastructure, CE solutions and manufacturing and maintenance. The development follows the guidelines of the design science research strategy.

The fourth subquestion “How can the developed strategic asset management support methods be evaluated in practice?” focuses on empirical testing of the developed decision support methods. Testing of the methods takes place during iterative rounds of development and evaluation. Some of the methods are utilized in a real or simulated decision context. Case studies are selected as the main method of evaluation.

Answers to the subquestions are presented in chapter 5.1. The outline of the publications is presented in chapter 1.4 and they are discussed in detail in chapter 4. All of the publications contribute to the first two subquestions, which aim to provide a holistic perspective of SAM support in organizations. Publications 3-6 provide novel methods for supporting SAM. Publications 3, 5 and 6 also include case studies in which the developed method is tested in practice.

1.3 Research process

The research process consisted of four phases (Figure 3).

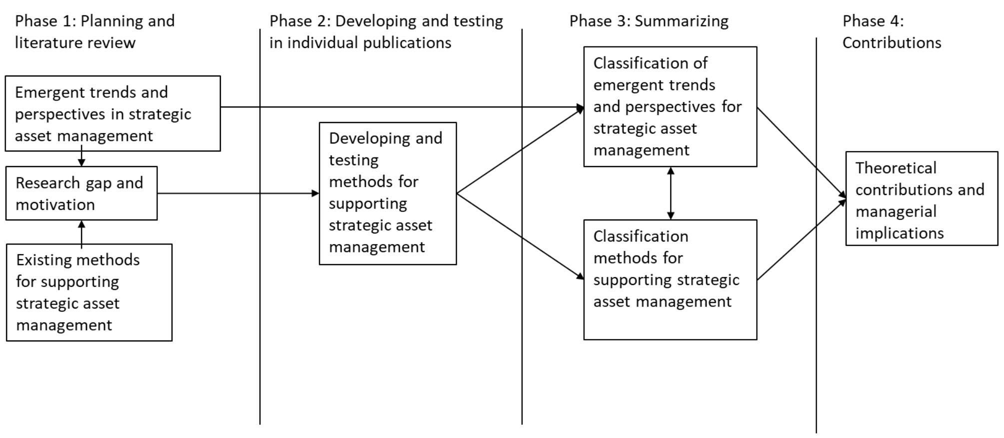


Figure 3. Research process.

The first phase of research was the background phase. During this phase, the key terms related to SAM were defined, and the main trends and perspectives affecting SAM and existing methods for supporting SAM were identified. The second phase consisted of developing and testing the individual methods for supporting SAM. The methods covered the important perspectives and trends and considered the existing decision support methods identified in phase 1. During the third phase, a classification of the most important trends and perspectives affecting SAM and the methods supporting SAM in the uncertain and complex decision context was developed. The final phase brought together the work of the previous phases and provided the managerial and theoretical contributions of the research. Additionally, it provided the summary part of the dissertation.

The research was conducted in several consecutive and overlapping research projects. All of the projects deepened the understanding of the perspectives and emerging trends that affect SAM. I was introduced to the concept of asset management in the Tekes (Finnish Funding Agency for Technology and Innovation, nowadays Business Finland (BF)) funded research project MaintenanceKIBS (2009-2012). The project involved two industrial companies and dealt with knowledge-intensive service development in the manufacturing sector. In this project I realized the importance of addressing sustainability issues in AM and the importance of understanding the needs of users and customers in AM service development. I continued working with AM in the Tekes-funded SerVesi project (2010-2013), which focused on risk management practices in the management of water and sewage sector assets and involved a university, three companies and a water and sewage service provider. During the project I was introduced to various types of decision support methods for AM, and publication 4 was written during it. I also led the demonstration work package in the EU-funded research project ToPDAd (Tool-Supported Policy Development for Regional Adaptation) during the years 2012-2015. This was a collaboration of ten research institutes and universities across Europe. In that project I delved deeper into the decision support systems for SAM and the impact of climate change on asset systems. Publications 5 and 6 were produced during the project.

Continuing my work on understanding sustainable business models in AM, I participated in the preparation of, and as a researcher in, the Tekes-funded StraSus project (2013-2015), a collaboration of four research institutes and universities and five companies. As a result, publication 1 was written. As a continuation of the StraSus project, I was then involved in the preparation of and as a researcher in the BF-funded D2W project (2016-2019). The focus of that project, involving three research institutes and five companies, was on role of information management in CE solutions and how AM supports CE. Publications 2 and 3 were written during this project. The present dissertation was also supported by the research conducted in the BF-funded SmartAdvantage project (2016-2018) and the Academy of Finland funded Digital Disruption of Industry (DDI) project (2016-2021), which focused on the digitalization of industry and AM services.

1.4 Outline of the original publications

An outline of the original publications is presented in Table 1.

Table 1. Outline of publications.

Publication	Author	Type, journal	Description
1. Strategic asset information management: experiences from Finnish companies	Jyri Hanski, Jere Jännes, Ville Ojanen, Pasi Valkokari	Koskinen K. et al. (eds.) Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015). Lecture Notes in Mechanical Engineering. Springer, Cham, pp 227-236. DOI: https://doi.org/10.1007/978-3-319-27064-7_22 (JUFO 1)	This paper focused on asset information management practices and sustainability in companies. The interview results were compared with the asset information management guidelines of the ISO 55000-2 (2014) standard.
2. Sustainability in strategic asset management frameworks: A systematic literature review	Jyri Hanski, Ville Ojanen	Accepted to be published in International Journal of Strategic Engineering Asset Management (JUFO 1)	The goal of the research was to determine the state of the art of methods for supporting complex long-term asset management decisions. The characteristics of existing strategic asset management decision support methods were analyzed.
3. Circular economy models – opportunities and threats for asset management	Jyri Hanski, Pasi Valkokari, Helena Kortelainen, Toni Ahonen	Proceedings of the Maintenance Performance Measurement and Management Conference (MPMM2016), 28 November 2016, Luleå University of Technology, Sweden, pp. 81-86.	In this paper, the impact of circular economy on asset management was analyzed. A method for assessing circular economy models from the asset management perspective was introduced.
4. Methods for value assessment of water and sewer pipelines	Jyri Hanski, Tiia Luomanen, Helena Kortelainen, Tero Välisalo	International Journal of Strategic Engineering Asset Management, Volume 1, Issue 4, DOI: 10.1504/IJSEAM.2013.060470 (JUFO 1)	This paper introduced the factors affecting strategic asset management in the water and sewage sector. A method for supporting strategic asset management decisions in the water and sewage sector was presented.
5. A method for visualization of uncertainty and robustness in complex long-term decisions	Jyri Hanski, Tony Rosqvist	Walls, L., Revie, M. and Bedford, T. (eds.) Risk, Reliability and Safety: Innovating Theory and Practice. Proceedings of ESREL 2016, CRC Press. DOI: 10.1201/9781315374987-445 (JUFO 1)	This paper presented a method for taking deep uncertainties and robustness into account in complex long-term strategic asset management decision situations. A case study in the renewable energy sector was presented.
6. Assessing climate change adaptation strategies – case of drought and heatwave in the French nuclear sector	Jyri Hanski, Tony Rosqvist, Douglas Crawford-Brown	Regional Environmental Change, Volume 18, Issue 6, pp. 1801-1813. DOI: https://doi.org/10.1007/s10113-018-1312-z (JUFO 1)	In this paper, a method for strategic asset management in complex long-term decision situations was described. A case study presenting the effects of drought and heatwave in the French nuclear energy sector was presented.

2. Theoretical background

This chapter compiles the concepts, trends and perspectives that have been examined in the publications included in this dissertation and in the asset management and other relevant literature. An overview of SAM is presented including in-depth analysis of the key concepts, perspectives, emerging trends and decision support methods of SAM. Firstly, the characteristics and definition of asset are discussed. Secondly, the different concepts linked to AM are discussed and the concepts of strategic management in organizations, uncertain and complex decision contexts, and SAM, are introduced. Thirdly, to understand the factors affecting SAM decisions, the perspectives and emerging trends of SAM are introduced. Fourthly, available decision support methods for SAM are presented.

2.1 Strategic asset management concept

This chapter focuses on introducing some of the key concepts used in this dissertation. These include asset, AM, strategic management in organizations, uncertain and complex decision context and SAM.

Asset

A variety of different asset types are identified in the literature (e.g. Hastings, 2010; Lei, Wijnia and Herder, 2012; ISO 55000-2, 2014). A basic distinction can be made between tangible or physical and intangible assets. Tangible assets can be divided into living workforce or human assets and non-living equipment, fixed assets, inventory, property, and engineering and infrastructure assets. Intangible assets are either financial, such as liability, equity, expense or current assets, or non-financial i.e. brand, reputation, lease, agreement, use right, license or intellectual property right. In addition, information or digital assets can be considered a specific asset category.

Focusing on physical assets, Hastings (2010) defines assets as “physical items such as plant, machinery, buildings, vehicles, pipes and wires” and the “associated information and technical control and software systems that are used to serve a business or organizational function.” Given their importance to modern production systems and infrastructures, the inclusion of information systems is a crucial addition to the definition. Striving for a general view, ISO 55000-2 (2014) defines asset as an “item, thing or entity that has potential or actual value to an organization.” The value can be tangible, intangible, financial or non-financial. In addition, the value includes consideration of risks and liabilities and may be positive or negative at different life cycle stages. Assets can be further characterized using the following distinctive features (van der Lei, Wijnia and Herder, 2012):

- **Function** of asset may be different for commercial, public or shared assets
- Asset **timescale or life cycle** can be short (one-use, weeks) or long (100 years) or something in between
- Fixed or moving **location of asset**
- Point, centralized or distributed **location of asset**
- **Economic** or **technical** assets
- External **environmental, social and financial** effects
- **Related technology**, e.g., mechanical, civil, electrical or software
- Timescale from the perspective of **life span** and **reaction time**
- Stable or dynamic **market behavior** of assets

- Fast or slow pace of **technology development**
- **Asset life cycle phase**, e.g., concept, design, manufacturing, assembly, commissioning, operation and maintenance, or disposal

This list illustrates the uncertainty and complexity related to the management of assets. In this dissertation the focus is on the management of physical assets. In particular, the focus is on complex assets or systems consisting of multiple assets.

Asset management and related concepts

ISO 55000-2 (2014) presents factors influencing the type of assets that an organization requires to achieve its objectives, and how the assets are managed: the nature and purpose of the organization and its operating context, financial constraints, regulatory requirements, and the needs and expectations of the organization and its stakeholders. As seen from the variety of asset types, AM has linkages to many different scientific and practitioner areas. As an example, ISO 55000-2 (2014) presents a list of standards that are linked to the subject areas of AM: data management, condition monitoring, risk management, quality management, environmental management, systems and software engineering, life cycle costing, dependability (availability, reliability, maintainability and maintenance support), configuration management, tero-technology, sustainable development, inspection, non-destructive testing, pressure equipment, financial management, value management, shock and vibration, acoustics, qualification and assessment of personnel, project management, property and property management, facilities management, equipment management, commissioning process and energy management.

Consequently, the definition of AM varies depending on, for instance, the scientific discipline, organizational decision-making level, maturity of AM practices, industry or asset type. Woodhouse (2006) presents some distinct uses for the term, as follows. In the financial service sector, AM describes the management of an investment portfolio or a stock aiming at the best mix of capital security, growth, interests rate, yield or other indicators, whereas main board directors use the term in relation to mergers and acquisitions. Equipment maintainers have adopted the term AM to gain greater credibility and respect and raise profile of maintenance on the corporate agenda. In line with the maintainers, also software vendors have labelled maintenance management systems as AM systems. In information systems, AM is interpreted as the tracking of the location or status of computers and other IT components. Critical infrastructure or plant owners and operators use AM to describe their business, i.e. investing in, exploiting and maintaining infrastructure or a plant over its life cycle. However, the world has changed since Woodhouse's definition in 2006 and new meanings have been since attached to the term AM.

There are several concepts related to AM. Physical asset management is a set of activities associated with identifying what assets are needed, identifying funding requirements, acquiring assets, providing logistic and maintenance support systems for assets, and disposing or renewing assets to effectively and efficiently meet the desired organizational objective (Hastings, 2010). Similarly, engineering asset management can be defined as the systematic, structured "process of organizing, planning and controlling the acquisition, care, refurbishment, and disposal of infrastructure and engineering assets." Additionally, it addresses the value contribution of AM to an organization's success (Amadi-Echendu et al., 2010; AAMCoG, 2012). Too (2012) presents a similar definition especially for infrastructure asset management, the "strategic and systematic process of optimizing decision-making in resources allocation with the goal of achieving planned alignment of an infrastructure asset with corporate goals throughout its lifecycle."

Facility asset management can be defined as "integration and alignment of the non-core services required to operate and maintain a business to fully support the core objectives of an organization" (Tucker and Pitt, 2009; Mangano and de Marco, 2014), whereas property asset management is "concerned with 'daily' administrative, technical and commercial management as well as maintenance activities" (Nieboer, 2005). Portfolio management focuses on the allocation of investments among asset options (ibid.). These definitions highlight the physical AM and life cycle perspectives. They focus on meeting organizational objectives or creating value. The definitions highlight the different decision contexts and application areas, i.e. what is considered important in infrastructure, financial and engineering asset management.

AM frameworks have shifted their focus away from a purely asset-centric view to one that considers the underlying purpose of owning and maintaining assets and demonstrating value generation through the provision of service (Marlow et al., 2007). Marlow and Burn (2008) define AM as "a combination of management, financial, economic, engineering, and other practices applied to (physical) assets with the objective of maximizing the value derived from an asset stock over the whole life cycle, within the context of delivering appropriate levels of service to customers, communities, and the environment, and at an acceptable level of risk." This definition covers the important strategic perspectives of stakeholder involvement, risk management, life cycle perspective, and value maximization.

The introduction of standards (IAM, 2008; ISO 55000-2, 2014) has somewhat unified the definitions of AM. PAS 55 (IAM, 2008) adds the element of systematic and coordinated practices in their definition: "systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan." ISO 55000-2 (2014) defines AM as the "coordinated activity of an organization to realize value from assets." AM involves balancing financial, environmental and social costs, opportunities, risks and quality of service against the desired performance of assets to achieve organizational objectives. In addition, it should consider the sustainability and the long-term competitiveness of the organization and take into account the effects on various external and internal stakeholders. This balancing might need to be considered over different timeframes.

Strategic management in organizations

Strategy can be simply defined as "the long-term direction of an organization." Strategy and strategic decisions are associated with an organization's scope of activity and competitive advantage, its strategic fit with the business environment, its resources and competences, and its values and expectations. Furthermore, strategic decisions are characterized by complexity, uncertainty, linkages to operational decisions, relationships and networks outside the organization, and change. (Johnson, Scholes and Whittington, 2008)

Strategic management aims to understand why some organizations perform better than their competitors (Kortelainen, 2011). A variety of methods exists for supporting strategic management in organizations (Clark, 1997). The most traditional approach for organizations to obtain sustainable competitive advantage is by exploiting internal strengths and responding to environmental opportunities, while also neutralizing external threats and avoiding internal weaknesses (Barney, 1991), i.e. SWOT analysis. The internal part of SWOT analysis, strengths and weaknesses, is based on resource-based view of competitive advantage (Wernerfelt, 1984; Barney, 1991). Resource-based view focuses on the links between the organization's internal characteristics and performance (Barney, 1991). According to the resource-based view, organizations are internally heterogeneous, which explains the performance differences between them (Kortelainen, 2011). The external part of the analysis, opportunities and threats, is, in turn, connected to environmental models of competitive advantage (Porter, 1985; Barney, 1991). In this line of analysis, the organization's competitive environment is analyzed and environmental conditions that favor high performance are identified (ibid.).

Strategic management can be divided into strategic position, strategic choices and strategy in action (Johnson, Scholes and Whittington, 2008). In this study, the focus is on strategic position and strategic choices. As this dissertation is not focused on the implementation of strategies, strategy in action is not discussed further.

Strategic position consists of external environment, strategic capability, purpose, and culture. External environment consists of, for example, economic, social, environmental and legal factors that affect the organization. Strategic capability refers to the strengths and weaknesses or competitive advantages and disadvantages of the organization. (Johnson, Scholes and Whittington, 2008). Strategic capability is connected to the resource-based view, whereas external environment is connected to environmental models of competitive advantage. Purpose includes aspects such as mission, vision, values, stakeholder expectations, corporate social responsibility and ethics (Johnson, Scholes and Whittington, 2008). Culture refers to aspects such as cultural and historical influences and organizational culture can be defined as values, beliefs, behaviors and taken for granted assumptions (ibid.).

Analysis of strategic position is followed by strategic choices. Strategic choices seek to determine decision alternatives that could best enable the firm to achieve its objectives (David, 2011). They include elements such as generation of strategic alternatives, evaluation of these alternatives and selecting an alternative(s) according to selected decision criteria (Johnson, Scholes and Whittington, 2008). The organization's present strategies, objectives, mission and external environment and internal capabilities provide a basis for generating and evaluating feasible alternative strategies (David, 2011).

There are an infinite number of decision alternatives and ways to implement those actions. Therefore, a manageable set of alternative strategies should be selected or developed. (ibid.). Performance of strategies may be evaluated through their advantages, disadvantages, trade-offs, costs, benefits, suitability, acceptability and feasibility (Johnson, Scholes and Whittington, 2008; David, 2011). The methods supporting strategic choices (strategic AM decisions) are presented in the following chapters.

Complex and uncertain decision context

The decision context determines what the decision is about (Salo and Hämäläinen, 2010). It covers all of the important factors affecting the decision and stakeholders affected by the decision. It includes the internal capabilities and external environment that are crucial to the decision. In decision situations, understanding the decision context is crucial as it may help in selecting and assessing decision objectives, alternative strategies and criteria against which the strategies are assessed. Clarification of the decision context is generally the first step in supporting decision-making.

Strategic decisions often deal with complex and uncertain decision contexts. Complex systems characteristically include large numbers of interacting elements with nonlinear interactions, are highly dynamic with a history that is integrated into the present, are subject to constantly changing external conditions, and also the actors and the system typically constrain one another, all of which present considerable challenges for forecasting (Snowden and Boone, 2007).

Uncertainty is the state of deficiency of information related to an event, its consequence, or likelihood (ISO, 2009). Uncertainty may refer to a lack of agreement among interested parties, lack of analytical approaches for analyzing the issue at hand, lack of knowledge about the state and trends of the parameters affecting the issue at hand, or a combination of these (Scrieciu et al., 2014). Decision situations such as land use change, depletion of resources, or climate change, may introduce extreme cases of uncertainty called deep uncertainty (Kasprzyk et al., 2013). In decision contexts involving deep uncertainties, decision makers do not know or cannot agree upon the full set of risks to a system or their probabilities (Lempert and Groves, 2010; Kasprzyk et al., 2013). Understanding uncertainty is critical in SAM as decisions can often have uncertain and major, long-term impacts on the actors involved.

Decision context can be divided into four different categories: simple, complicated, complex and chaotic (Snowden and Boone, 2007). A simple decision context requires straightforward management and monitoring and strategic responses are based on established practices. In a complicated decision context, several competitive decision options have to be analyzed and expertise is required to understand the decision options and their consequences. In a complex decision context, the consequences of decisions can be understood only in retrospect. A complex decision context requires experiments, sensing the impacts of the experiments, and responding to the differences between expectations and reality. This is in line with the principles of adaptive management presented in the following chapter. A chaotic decision context is unpredictable and the causal relationships are not known. No manageable patterns exist and the effects are impossible to determine.

Due to complexity and uncertainty, strategic agility and flexibility are emphasized to quickly react to changes in the market (Raynor, 2007; Doz and Kosonen, 2008). In the management of uncertainty, strategic management has been influenced by the practices of high-reliability organizations, such as in the nuclear sector or military aircraft carriers (Weick and Sutcliffe, 2001). These practices include careful analysis of failures and near misses, striving for holistic understanding of situations, sensitivity to anomalies in operations, a focus on resilience, and deference to expertise instead of hierarchy.

This dissertation focuses predominantly on strategic decisions that take place in complex and uncertain decision contexts. The sources of complexity and uncertainty are discussed at length in the following chapter.

Strategic asset management

A strategy is a plan that guides how an organization intends to achieve its objectives, and it should also specify the procedures to be followed in managing its assets (Hastings, 2010; ISO 55000-2, 2014). SAM specifies how organizational objectives are converted into AM objectives (ISO 55000-2, 2014). SAM is influenced by the organization's plans, objectives and strategic decisions which, in turn, are influenced by the stakeholders and the organizational context. Top management, employees and stakeholders are involved in the creation and monitoring of SAM policies and processes. The alignment of SAM objectives and organizational objectives can improve the performance of an organization (ISO 55000-2, 2014). SAM should be systematic and comprehensively consider, for example, technical, social and financial aspects, and long and short-term objectives (Nieboer, 2005). Komonen, Kortelainen and Räikkönen (2012) argue that the AM strategy is a function of: (1) values, vision, objectives, and strategy, (2) technology in use, (3) strategic position and other characteristics of the company, and (4) characteristics of relevant markets.

SAM deals with issues such as whether assets should be enhanced by capital investment, maintained to sustain their position in the asset system, or be disposed of. In addition, it exploits other asset options such as mergers, real options, outsourcing and restructuring of the production system. (Komonen, Kortelainen and Räikkönen, 2012). Other identified issues include considering opportunities within the wider asset portfolio, value-add and reuse opportunities, policy questions and project constraints (Povey and Peach, 2013). AM strategy is linked with the concept of maintenance strategy. Especially on the corporate level, a maintenance strategy might deal with SAM-related issues such as what kinds of maintenance management models should be used in which countries and for what kinds of equipment, and whether some areas of maintenance should be outsourced.

The concept of AM presented in ISO 55000-2 (2014) covers the key elements of SAM. The general and holistic definition presented by ISO 55000-2 (2014) applies also to SAM. However, in order to focus the definition on only strategic-level activities, instead of the operative, tactical and strategic levels, a slight modification is needed. Therefore, the definition of SAM in the context of this dissertation is as follows: "*strategic-level* coordinated activity of an organization to realize value from assets."

2.2 Perspectives and emerging trends in strategic asset management

As seen from the multitude of asset types and definitions, SAM can be viewed from several different perspectives and is affected by several trends. These trends and perspectives highlight the complexity and uncertainty related to SAM decisions and set requirements for the development of decision support methods for SAM. The selected perspectives and trends have been addressed in the publications included in this dissertation and are considered key emerging trends and perspectives affecting SAM. The perspectives and trends are classified into external and internal views. The views are derived from the strategic management schools of environmental models of competitive advantage (external view) and resource-based view (internal view).

2.2.1 Strategic asset management: external view

The external view consists of the key trends and perspectives that shape the operating environment of an organization. According to ISO 55000-2 (2014), the external view includes factors such as the social, cultural, economic and physical environments, and regulatory, financial and other constraints. Based on the publications in this dissertation and other relevant research, the external view of SAM is extended by including the following key emergent perspectives and trends: the regulation, legislation and stakeholder perspective; sustainability; circular economy; climate change; the technology perspective and digitalization; the ecosystem, market and customer's decision context perspectives; and servitization.

Regulation, legislation and stakeholder perspective

Regulation, legislation and stakeholders play a major role in SAM decisions as they set a range of requirements for SAM. SAM activities often involve multiple stakeholders and increasingly complex network structures. Stakeholder input is a part of the organizational context and instrumental in setting rules for consistent decision-making (ISO 55000-2, 2014). Asset-related decisions should be made according to a single set of stakeholder-driven criteria (Brown and Humphrey, 2005). Stakeholder can be defined as an "individual or group that has an interest in any decision or activity of an organization" (ISO 26000, 2010). Traditionally, decisions related to policy-making and critical infrastructure, such as water, electricity, heat, gas, roads and railways, have been of special interest to external stakeholders. The availability of these systems has severe impacts on most private and public sector actors. Stakeholders identify policy solutions and play a key role in policy learning (McAllister, McCrea and Lubell, 2014).

The design of new asset systems and redesign of existing systems involves many uncertainties. For instance, SAM decisions on infrastructure are subject to rapid technological changes and institutional and economic developments, such as deregulation, liberalization and changes in the cost of raw materials (Herder and Wijnia, 2012). Table 2 highlights the key issues in infrastructure design and replacement. For the asset system to operate well there must be coherence among technical and institutional systems on all layers (Finger, Groenewegen and Künneke, 2005; Jonker, 2010; Herder and Wijnia, 2012).

Table 2. Temporal layers of the strategic asset management decision context. Adapted from Bauer and Herder (2009) and Herder and Wijnia (2012).

Time scale	Social system	Technical system
Embeddedness: changes 100 to 1000 years	Informal institutions, customer, traditions, norms, religion	Informal conventions embedded in technical artifacts
Institutional environment: changes 10 to 100 years	Formal rules of the game (property, polity, judiciary, etc.)	Technical standards, design conventions, technological paradigms
Governance: changes 1 to 10 years	Play of the game (contract and governance transactions)	Protocols governing operational decisions and best available technology
Operation and management: continuous adjustments	Prices, quantities, incentives	Operational decisions

Sustainability
Stakeholders are increasingly demanding that organizations follow sustainability principles and sustainability is, consequently, on the strategic agenda of many organizations. Adopting the sustainability paradigm sets new requirements for SAM operations. The goal of sustainability is to meet present needs without compromising ecological systems, social justice, or the welfare of future generations (Brundtland, 1987; Jorna, Hadders and Faber, 2009). Epstein and Roy (2003) and Epstein (2008) present a set of principles to help organizations focus on sustainability in their decision-making processes: ethics, governance, transparency, business relationships, financial return, community involvement and economic development, value of products and services, employment practices and protection of the environment.

There are several reasons why aspects of sustainability demand the attention of organizations. Noncompliance with regulations can be costly through, for example, fines, legal costs and effects on the company's reputation (Epstein, 2008). Community relations are important in order to gain the loyalty and trust of various stakeholders (Keeble, Topiol and Berkeley, 2003; Epstein, 2008; Lackmann, Ernstberger and Stich, 2012). Sustainability may also bring greater revenues and lower costs through enhanced reputation and a reduction in fines and other costs (Epstein, 2008). Additionally, sustainability can be a source of competitive advantage and value creation (Elkington, 1998; Schaltegger and Wagner, 2006).

SAM plays a major role in moving towards sustainability (e.g. Marlow, Beale and Burn, 2010; ISO 55000-2, 2014). ISO 55000-2 (2014) emphasizes the environmental, economic, and social pillars of sustainability. However, for SAM, expressing sustainability in clear and concrete operational terms has been challenging (Labuschagne, Brent and Van Erck, 2005; Liyanage and Badurdeen, 2010). Additionally, there is a lack of guidance addressing the importance of SAM in achieving sustainability (Ojanen et al., 2012). Some sectors, such as water supply, are intrinsically engaged in achieving sustainability outputs due to strong emphasis on financial efficiency, meeting legislative requirements and improving public health and the environment (Marlow, Beale and Burn, 2010). However, Marlow, Beale and Burn (2010) add that water sector actors do not necessarily operate according to broader sustainability principles (e.g. more focus on saving water on the demand side).

Circular economy
Strategies and solutions that extend the life cycle and conserve the value of materials offer much potential (Ness and Xing, 2017). CE is a rising trend and a means for promoting sustainability in organizations. CE can be defined as a system that creates value by minimizing waste, energy and use of natural resources (Geissdoerfer et al., 2017). It is has similarities with approaches such as closed-loop, resource efficiency and productivity, optimization of use of goods and assets, longevity and durability, industrial economy and symbiosis and life cycle assessment (Ness and Xing, 2017).

CE is seen as beneficial not only from the environmental and social perspectives but also from the economic perspective (Tura *et al.*, 2019). A shift to a CE is estimated to reduce each European nation's greenhouse-gas emissions by up to 70% and grow its workforce by about 4% (Wijkman and Skånberg, 2015; Stahel, 2016). Adopting CE principles would generate a net economic benefit of EUR

1.8 trillion by 2030 (Ellen MacArthur Foundation, SUN and McKinsey Center for Business and Environment, 2015).

SAM and CE have many similarities – they both aim at the optimization of resource or asset value over the full life cycle. However, whereas CE aims at extending the use of assets and resources beyond the initial life cycle in similar or different use situations to maximize the efficiency of resource usage and at replacing non-renewables with renewable materials, SAM considers multiple decision criteria, including economic and risk perspectives, when assessing solutions. Therefore, not all CE solutions may be viable from a SAM perspective.

Climate change

Efficient consumption of resources is also crucial for reducing greenhouse gas emissions. Mitigation, i.e. reducing the sources and enhancing the sinks of greenhouse gases, is a crucial way to fight climate change (CC). Climate change can be referred to as “any change in climate over time, whether due to natural variability or as a result of human activity” (IPCC, 2014). Kortschak and Perrels (2013) classify CC impacts into four categories: slow and fundamental changes in natural conditions; extreme weather-related events; ecosystem collapses due to slower underlying trends; and atypical seasonal weather patterns (decreased seasonal predictability).

Reducing greenhouse gas emissions has been a fundamental part of the European Union’s CC policies, but the need for CC adaptation strategies is also recognized (e.g. EC, 2013). Adaptation is considered important because the effects of CC are likely to occur even if mitigation targets are met (Swart et al., 2009). The IPCC (2014) defines adaptation as “the process of adjustment to actual or expected climate and its effects.”

CC mitigation and adaptation targets should have a major impact on SAM strategies. SAM needs to adapt and respond to the requirements of changing natural conditions and extreme weather events. Electricity production is an example of CC impacts that affect SAM. If CC is not addressed, the efficiency of electricity generation may be significantly reduced due to decreased availability of water for cooling power stations during periods of drought, and restrictions on the return of water to rivers that are already at a high temperature due to extended heatwaves (Aaheim et al., 2013; EC, 2013).

Technology perspective and digitalization

Technology has an essential impact on the effectiveness of AM strategy (Komonen, Kortelainen and Räikkonen, 2006; 2012). Komonen and colleagues (ibid.) also argue that the flexibility of original investment, economic and technical inertia, and relative length of the economic and technical useful life of equipment are some of the main elements that determine the technological capabilities that are required to meet market needs.

SAM is affected by technological advances in different fields such as cyber-physical systems, virtualization, artificial intelligence, cloud computing, increased instrumentation and data collection, robotization, nanomaterials, biotechnology, energy technology, digital platforms and blockchain technology. Digital transformation or digitalization is a major global trend that is transforming many sectors, including asset-intensive sectors such as manufacturing, energy, and a range of public services (OECD, 2015; WEF, 2015). A common definition of digitalization by Gartner (2018) is “the use of digital technologies to change a business model and provide new revenue and value-producing opportunities." Digitalization is closely linked with other buzzwords describing advances in digital technologies, such as the Internet of Things (IoT), Industry 4.0 and the Industrial Internet.

Novel products that are based on digital technologies require a new multi-layered technology infrastructure consisting of different platforms, programs, networks, services, processes, and actors (Porter and Heppelmann, 2014; Juhanko et al., 2015). With digital platforms and applications, sensor and process information can be more extensively and effectively used to support SAM-related decision-making. Digitalization enables new ways to manage maintenance, repair and field operation, and improve product and service development (Baines and Lightfoot, 2014). In the future, Lee, Bagheri and Kao (2015) have also envisioned intelligent, resilient, and self-adaptable machines and truly digital production systems.

Ecosystem perspective

Organizations operate in complex, dynamic and adaptive business networks involving multiple actors to provide products and services to their customers. Assets produced by original equipment manufacturers (OEMs) are often located at different customer sites and locations. Asset-related products and services are often based on data, competence and other resources owned and operated by a variety of actors and stakeholders. These networks are often called ecosystems. Ecosystems can be defined as "dynamic, purposeful and value-creating interconnected networks in which the participants co-create value by having a shared goal" (Adner, 2006; Adner and Kapoor, 2010; Ritala, Almpanopoulou and Blomqvist, 2017). In addition to the business context, the ecosystem perspective is utilized in sustainable development, information technology, innovation, and industrial ecosystem research (Kinnunen et al., 2017).

The importance of digital platforms is increasing. Research has moved from supplier–customer relationships to service ecosystems and value co-creation through digital platforms (Vargo and Lusch, 2011; Lusch and Nambisan, 2015). Digital platforms have the potential to change relationships in ecosystems and introduce new actors, such as platform providers and information brokers. Digital platforms are utilized in the development and maintenance of new products and processes in order to maintain compatibility with previous, present and future product generations and ecosystems (Juhanko et al., 2015). Utilizing digital platforms is a source of competitive advantage for organizations, and those failing to move into new business models enabled by platforms may lose their competitiveness.

Market perspective

SAM decisions are influenced by the structure and characteristics of the market in which the organization operates and are attuned to market demand (Nieboer, 2005). Some of the main market characteristics are: phase of industrial development, asset-related barriers to entry, industry uncertainty and volatility, sources of differentiation, and regulatory acts (Komonen, Kortelainen and Räikkonen, 2006;2012). Komonen et al. (ibid.) further argue that market characteristics have a major impact on the flexibility requirements of assets and SAM.

In many sectors, digitalization is blurring and dissolving the market boundaries that once specified the relationships and interactions within them (Kelly, 2015). Due to this boundary blurring, the categorization of specific markets is becoming more difficult. Therefore, SAM should pay attention to the changes in the market and their implications for AM strategies.

Customer's decision context perspective

The importance of the customer and customer needs in strategic management has long since been highlighted by Drucker (1954) and Levitt (1960). Organizations often develop solutions based on what they perceive would be valuable to their customers. However, their idea of customer needs might differ from that of the customers and users themselves. Solutions that make sense from the service provider's perspective can fail due to lack of consideration of the decision context of the customer. Ahonen, Hanski and Uusitalo (2018) provide two common examples of this mismatch: increasing the availability of a production system that has a wide maintenance window, and increasing the reliability of non-critical systems – neither of these actually benefit the customer.

Therefore, when providing AM services, understanding the customer's decision context is crucial. The organization needs to know what decision-making situations their customers face, and in what situations can the customers benefit from the offered services (Kunttu et al., 2016). There are many complementary categorizations of AM decision situations. In general, AM decisions are made at the operative, tactical and strategic levels. Similarly, for asset-intensive process or manufacturing companies, decision situations can be categorized as corporate, plant and equipment level AM decisions (Komonen, Kortelainen and Räikkonen, 2006; 2012). These categorizations allow the separation of routine decisions from decisions with long-term effects on the whole organization (Kunttu et al., 2016; Ahonen, Hanski and Uusitalo, 2018). Operative-level decisions typically occur frequently, and must be made quickly. At the tactical level, decision situations are more complex and have a greater impact on business performance than decisions made at the operational level. At the strategic level, decision situations are highly complex and have long-term implications for business profitability, and are supported by various decision-support methods. Ahonen, Hanski and Uusitalo (2018) accentuate the differences between the decision-making levels in Table 3.

Table 3. Customer's decision context at different decision-making levels. Adapted from Ahonen, Hanski and Uusitalo (2018).

	Operative level	Tactical level	Strategic level
Objectives	Daily operation and maintenance	Development of current assets or functions to improve business profitability	Changing current assets or functions to improve business profitability
Constraints	Selected maintenance strategy, maintenance windows, criticality of equipment	Company-level strategic choices, maintenance windows, and criticality of equipment	Operating environment, and company-level vision, values, mission, and strategic choices
Example of user or decision maker	Operators, maintenance technicians, managers	Management	Leadership
Example of decision situation	Focusing maintenance actions on right assets and problems; Timing of maintenance actions; Resource planning	Replacement investment, maintenance strategy formulation	Moving into new business, market, or technology; Investment in a new production line/plant
Business impact of decisions	Seldom crucial	Moderate to major influence on profitability of business	Major influence on profitability of business

Furthermore, decision situations can also be classified according to the asset life cycle phase in which the decisions are made. They can be reactive, real-time, proactive, or strategic decisions by nature (Kortelainen et al., 2017a). Additionally, decision situations are classified using the relevant time scale (Sun, Fidge and Ma, 2009) and asset type (Wijnia, 2016) as criteria.

Servitization

Lately, asset-intensive companies have been adopting more service components into their formerly product-centric offering (Baines et al., 2007; Baines and Lightfoot, 2014; Lerch and Gotsch, 2015). This development is called servitization. A manifestation of servitization is expanding the offering to product–service systems (PSS). A PSS can be defined as an integrated bundle of products and services that aims at creating customer utility and value (Boehm and Thomas, 2013). Digitalization is an opportunity and enabling trend for servitization (de Senzi Zancul et al., 2016). Servitization offers opportunities for extending the service offering by enabling the service provider to monitor and gather data during the life cycle of the product (Hanski, Kortelainen and Uusitalo, 2018).

One of the primary goals of SAM is to meet the required level of service for present and future customers (IPWEA, 2006). Servitization offers new opportunities to fulfill customer needs and extend the service delivery over the whole life cycle of assets. Servitization is considered an enabling factor for increased sustainability and CE solutions (Lacy and Rutqvist, 2016).

2.2.2 Strategic asset management: internal view

According to ISO 55000-2 (2014), the internal view includes the organizational culture and environment, as well as the mission, vision and values of the organization. In this chapter, based on the publications in this dissertation and other relevant research, these perspectives are complemented with the following internal perspectives related to SAM: business models, risk management, information management, life cycle and fleet management, robustness, and adaptive management and flexibility. Some important additional perspectives that were not focused on in the publications are also presented.

Business model perspective

The business model describes the rationale for how an organization creates, delivers and captures value (Osterwalder and Pigneur, 2010). A successful business model excels in three main dimensions: value creation, value proposition and value capture (Clauss, 2017). Value creation consists of capabilities, technology, partnerships and processes needed for the solution. The value proposition depicts the content of the service including the offering, customers and markets, channels and customer relationships, whereas value capture includes the revenue model and cost structure (Osterwalder and Pigneur, 2010; Clauss, 2017).

A suitable business model is a prerequisite for successful AM services. Without it, the value is not transmitted to the customer and the revenue will not be provided to the supplier (Chesbrough, 2010; Ojanen et al., 2012). In the SAM context, business models traditionally apply especially to outsourced AM services such as maintenance, operation and decision support services. Rekola and Haapio (2009) classify the value propositions of maintenance services ranging from price-focused short-term maintenance contracts to availability-based contracts and finally to long-term value partnerships. Ahonen, Hanski and Uusitalo (2018) present new types of maintenance value propositions enabled by digital technologies and advanced analytics competencies. These include provision of a service platform and enabling technologies, analytics-based services such as diagnostics, predictive maintenance and predictive performance management, and asset performance services such as supporting the optimal management of assets with a combination of relevant data, advanced analytics and domain knowledge.

Risk management perspective

Risk management can be defined as "coordinated activities to direct and control an organization with regard to risk." In this context, risk is defined as the "effect of uncertainty on objectives," where effect is a positive or negative deviation from the expected. Objectives can have, for example, financial, environmental or safety aspects and be applied at different levels, such as strategic, product or process. Risk is often expressed as a combination of the consequences of an event and the likelihood of occurrence (ISO, 2009). Risk management aims to create transparency inside and outside the organization, enhance risk awareness, minimize the probability of future losses, maintain preparedness and ensure protection against adverse events, and maximize the probability of success and minimize the risk of failure in reaching organizational objectives. It is a continuous management process where exposures are systematically identified, evaluated and managed (Andersen and Terp, 2006.)

Risk management should be an integral part of the strategic planning process (ibid.). It is also a central part of SAM. The organization should consider the significance of the risks identified (ISO 55000-2, 2014). The role of risk management in SAM is emphasized in managing complex asset systems, such as infrastructures. At the operational phase of infrastructure, their SAM is essentially risk management, i.e. managing the risk of the system not functioning as designed. Risk management requires understanding the values at risk and all risks in the system, and optimizing risk mitigations (Herder and Wijnia, 2012). Risk-based asset management approaches have recently been developed for the infrastructure sector (e.g. Mehairjan, 2016; Wijnia, 2016).

Information management perspective

Information management is a crucial part of SAM. Information management in the context of SAM refers to perspectives such as data quality and value (Ouertani, Parlikad and McFarlane, 2008), documentation and reporting (MacGillivray and Pollard, 2008), data integration (Brimfield and Myers, 2011), asset knowledge management (Kersley and Sharp, 2014), systems for capturing and storing asset data, and information management processes (Haider, 2012).

Information management consists of activities such as data collection, data pretreatment, descriptive data analysis, data modelling and utilization of information, knowledge or wisdom to support business decisions (Kunttu et al., 2016; Kortelainen et al., 2017a). Regarding data collection, ISO 55000-2 (2014) emphasizes the importance of determining information needs, the value and quality of information in relation to the costs of obtaining and utilizing it, the definition of data collection and management processes, and the availability of AM information to support decision-making. Regarding the analysis and utilization of asset information, ISO 55000-2 (2014) highlights the importance of defining, implementing and maintaining methods for analyzing and evaluating asset information. Additionally, processes for where and how the data is transformed into usable information and how it will be communicated should be defined. Finally, the organization should consider the need to align information requirements to suit the level of risk that an asset poses (ISO 55000-2, 2014).

Asset-related data is typically vast, multifaceted and fragmented across many information systems and documents. The use of data that is larger than can be utilized in common software applications, i.e. big data, has also become of interest in SAM. Big data can be classified with 4 Vs: great Volume, various modalities (Variety), rapid generation (Velocity), and huge Value but very low density (Chen, Mao and Liu, 2014). In addition, decision situations at the strategic, tactical and operative levels typically have different information needs. Unnecessary duplication of data should be avoided and the data should reside in the information system that is most appropriate (ISO 55000-2, 2014). Asset systems are also more complex than ever and require advanced knowhow to operate them and prevent component, machine and system breakdowns (Kortelainen et al., 2017b).

Digitalization has the potential to revolutionize the information management process. The role of the information management system is emphasized in complex asset systems with many actors and stakeholders. In this case, the asset owners should consider making their asset system more transparent to other companies in the network. This is in line with ISO 55000-2 (2014), which highlights the ease of information exchange with service providers, the use of common terminology, and collaboration with relevant stakeholders. For instance, suppliers might have a direct link with the procurement process of their customers in order to capture orders for sub-assemblies, which would also help in planning their own resource use and orders for components and raw materials (Baines and Lightfoot, 2014).

Life cycle and fleet management perspectives

A life cycle can be defined as a “series of stages through which an item goes, from its conception to disposal.” A life cycle typically includes acquisition, operation, maintenance, modernization, decommissioning and/or disposal phases (EN, 2017b). Life cycle management is a crucial AM task, for which the definition of life cycle management tasks and information requirements is highly beneficial (Hanski and Valkokari, 2018). Strategic decisions in the early design phase have a considerable effect on the whole life cycle of an asset (Mileham et al., 1993; Tiusanen and Jännes, 2017). Due to the emergence of sustainability and CE requirements, the end of life phases of assets is becoming increasingly important.

Fleet management refers to the management of a set of systems, subsystems and components that have similar or nearly similar characteristics (Kortelainen et al., 2017a). Fleet management addresses, for instance, the management of the installed asset base of a globally operating machinery manufacturer (Ahonen et al., 2010). Fleet management solutions have been enabled by the development of digital technologies. Through digitalization, organization may access, collect and analyze data streams from machines and infrastructure items located anywhere. There are three types of machinery or component fleets: identical, similar, or heterogeneous (Medina-Oliva et al., 2014), which poses challenges for data analysis and utilization. Fleet-based information may be used, for example, for assessing the performance of a single machine compared to the current and previous performance of the entire fleet (Lee, Bagheri and Kao, 2015).

Kortelainen et al. (2017a) highlight that the fleet management based solutions should have value for asset owners or other crucial stakeholders. Asset owners call for solutions that maximize the value extracted from the assets deployed in their systems, whereas service and equipment providers have the potential for providing value-added services for the asset owners based on fleet-level knowledge.

Robustness perspective

To answer to the uncertainties introduced by the long lifetimes of assets, multiple stakeholders, and changes in the operating environment, there is a need for strategies that are robust under several different scenarios. In complex and uncertain decision contexts there is usually agreement regarding the set of scenarios; which variables are included, which time frame is considered, and how many scenarios will be enough to represent the future pathways. There is, however, less agreement about the performance levels and related value of the strategies. Therefore, there is a need for revealing this particular uncertainty in order to identify whether there is a strategy that would indicate robustness or vulnerability. A robust strategy can be defined as a strategy that, in comparison to the alternatives, performs relatively well across a wide range of plausible futures (Lempert et al., 2006). Robust solutions are beneficial especially for long-term investments (Berkhout et al., 2014)

Adaptive management and flexibility perspectives

Adaptive management is an alternative and also a complementary approach to robust strategies in response to uncertainty. Its goal is to enhance system resilience by flexible, learning-oriented and experimental management (Fritsch, 2017). Adaptive management assumes that the future will in part evolve in unanticipated ways. In adaptive management, strategies are based on current knowledge and predicted conditions, but must be flexible for adaption to future conditions as these emerge, thereby promoting a continual learning process (Hamilton et al., 2013). Therefore, a decision-maker does not develop a strategy that will remain in place for decades, but rather uses the current scientific knowledge to develop strategies that will remain in place for a short time, and then adjusts these strategies as the future unfolds. Adaptive management should be considered at the design phase of assets to provide technical and budget flexibility to ensure the adaptation of the initial design to changing requirements (Herder and Wijnia, 2012).

Flexibility in the face of changing circumstances is a key feature of any adaptive management strategy. Adger, Arnell and Tompkins (2005) define flexibility as the "ability to change in response to altered circumstances." Triantis (2003) proposes ways to maintain flexibility with respect to solutions. For instance, linking solutions with other solutions minimizes implementation and transaction costs, finding solutions that can be justified for a broad range of scenarios, and making solutions switchable and scalable, thus avoiding rigid one-time investments that produce 'lock in'. Other suggested ways include waiting for better information and assessments, or for opportunities not foreseen right now. Flexibility is identified as an important AM system decision criterion in some applications (Komonen, Kortelainen and Räikkönen, 2012; van der Lei, Wijnia and Herder, 2012).

Additional important perspectives
The list of perspectives and emerging trends presented in this chapter is by no means exhaustive. Additional important factors to be considered include, for instance, RAMS, systems engineering, quality of processes, and organizational and human factors.

The fundamental goal of AM is to produce value by keeping assets in operation. To ensure the safe and reliable operation of assets approaches such as systems engineering and RAMS are crucial. Systems engineering is an approach that guides the engineering of complex systems and addresses the system as a whole, i.e. the total operation of system over its life cycle (Kossiakoff and Sweet, 2003). SAM is linked with RAMS management, i.e. management of the Reliability, Availability, Maintainability and Safety aspects of a system. Reliability is the "ability to perform as required, without failure, for a given time interval, under given conditions" (IEC, 2014). Availability can be defined as the "ability to be in a state to perform as required" (IEC, 2014). Safety is defined as "freedom from unacceptable risk of harm" (EN, 2017a) and maintainability as the "ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance" (IEC, 2014).

Organizational factors and the quality of processes and activities are together the backbone of SAM. Organizational factors include some of the perspectives included in internal and external view of strategic management, such as information management and market perspective, but also internal and external coordination, processes and roles, training and culture and leadership (Hastings, 2010; Volker et al., 2014). ISO 55000-2 (2014) highlights the importance of considering roles and responsibilities for AM, the AM processes, procedures and activities. The role of human factors and people management is highlighted in SAM (e.g. Harpur and Brown, 2012; van der Lei, Wijnia and Herder, 2012).

2.3 Decision support methods for strategic asset management

This dissertation focuses on strategic decision support methods. In this dissertation, strategic decision support methods refer to general qualitative and quantitative methods that support decision-makers in their strategic decisions. These methods often involve the use of expert opinion and analyses, and they are rarely the sole means for supporting decisions. Therefore, methods supporting tactical and operational level decision-making are not in the scope of this study. SAM methods help an organization to plan, manage and develop their or their customer's AM system and practices. The methods typically assess the performance of the organization using a set of indicators and include measures of uncertainty. SAM covers a variety of asset types that are managed in different decision contexts using various AM strategies. Organizations face several trends that necessitate the development and utilization of more comprehensive and analytic approaches to SAM decision-making (Komonen, Kortelainen and Räikkönen, 2012). These trends and perspectives are discussed at length in the previous chapter. Considering this, it is not surprising that SAM may be supported by a variety of different decision support methods.

2.3.1 Classification of decision support methods

There are multiple classifications of methods supporting SAM. Based on the complexity of the decision context, AWWARF (2001) classifies the methodologies for the water sector as follows: voting for simple cases; a spreadsheet with weighted evaluation criteria, performance measures, and project ranking for complex cases; and multi-criteria decision analysis for the most complex cases with multiple stakeholders with conflicting interests. Additionally, the decision situation may dictate the type of method used for decision support. For water sector SAM, a different decision support method could be applied in the case of measuring network value during mergers and acquisitions and in renovation planning. Shafiee et al. (2019) focus on the oil and gas industry and identify a list of decision support methods including operational research, CBA, real options analysis, LCC, environmental life cycle assessment, Monte-Carlo simulation, decision tree analysis, MCDA, fuzzy logic analysis and artificial intelligence.

Uncertainty and complexity of the decision context are major factors affecting the selection of decision support method. Decision situations may involve multiple stakeholders with possibly conflicting objectives, complex assets and asset systems and long timeframes. For uncertain and complex decision contexts, such as climate risk assessment, UNFCCC (2010) identifies the following decision support approaches and methods: cost-benefit analysis, cost-effectiveness analysis, multi-criteria decision analysis, portfolio theory and real options, pathway analysis, adaptive capacity assessment, risk management methods, scenario-based approaches, technological assessments, normative policy assessments, identifying learning in organizations, participatory techniques, and social learning. Similarly, in a climate change adaptation context, Watkiss et al. (2015) divide decision support methods into traditional decision support (CBA, cost-effectiveness analysis and MCDA) and decision-making under uncertainty (real options analysis, RDM, portfolio analysis and iterative risk management).

The life cycle of assets plays a crucial role in determining the decision support method. As an example, Herder and Wijnia (2012) categorize SAM decision support according to methods for managing existing infrastructures, and designing and replacing infrastructures. Managing existing infrastructures emphasizes a risk-based approach that focuses on optimizing the AM process instead of optimizing the assets. Examples of methods for designing and replacing infrastructures include using RAM models, real options and serious gaming.

The choice of decision support method is limited by the availability of data. Quantitative, data-intensive methods cannot be utilized if there is no data available. If a complex methodology and analytics are used, specific methodology and analytics expertise is needed. In addition, there might be a need for domain or asset related expertise to provide expert opinion based data or to evaluate the results of the method. Finally, the choice of decision support method may be limited by the resources available for the analysis.

2.3.2 Methods for supporting strategic asset management in complex and uncertain decision contexts

There are several methods for tackling complex and uncertain decision contexts in SAM. Methods include continuous improvement and assessment (Amaratunga, Sarshar and Baldry, 2002; Mehairjan et al., 2012; Attwater et al., 2014), risk assessment methodologies (Kramer and Peppelman, 2012; van der Lei, Wijnia and Herder, 2012; Sun, Ma and Mathew, 2013; Attwater et al., 2014), portfolio management (Kramer and Peppelman, 2012), real options and serious gaming (van der Lei, Wijnia and Herder, 2012), multi-criteria decision analysis methods (MCDA) (MacGillivray et al., 2007; MacGillivray and Pollard, 2008; Parida, 2012; Volker et al., 2014) and scenario methods (Hall et al., 2004; Nielsen, Chattopadhyay and Raman, 2013). To evaluate decision alternatives, criteria such as risk, uncertainty, volatility, and flexibility can be used (e.g. Komonen, Kortelainen and Räikkönen, 2012; Stapelberg, 2012). Methods supporting uncertainty management include expert elicitation, Monte Carlo analysis, multiple model simulation, weighting methods, scenario analysis, sensitivity analysis and stakeholder involvement (e.g. Hall et al., 2004; Refsgaard et al., 2007; Chemweno et al., 2015). For planning under deep uncertainty, three alternative approaches are suggested: resilience, robustness and exploratory modelling (Thissen et al., 2017). In the following, a list of methods for supporting SAM in complex and uncertain decision contexts is introduced.

Key performance indicators, guidelines and checklists

SAM development is supported by the identification, development, and implementation of appropriate guidelines and key performance indicators (KPIs) (Parida et al., 2015). KPIs are derived from the organizational strategy and should guide the SAM development (Leidecker and Bruno, 1984; Tsang, Jardine and Kolodny, 1999; Parida et al., 2015). They refer to a list of indicators for monitoring and improving AM and performance. Salonen and Bengtsson (2011) present a list of company-specific non-monetary KPIs related to overall company, production, and maintenance goals such as work-time distribution, overall equipment effectiveness, and technical availability.

As an example from the water and sewage sector, indicators of network condition include factors such as internal and external load, manufacturing and logistics, quality of installation and implementation, quality of work, and durability of pipe materials and instruments. Generally used KPIs for the water and sewage sector include the amount of water that cannot be invoiced to the customers, amount of leakages of water or blockages in the sewer system, the number of unexpected leakages that need repairing, and interruptions to water distribution.

Benchmarking

Benchmarking was introduced in the early 1990s (Åhrén and Parida, 2009). It provides a basis for learning from the forerunner organizations, offers a roadmap for performance improvement and supports the management in their pursuit of continuous improvement of their operations (ibid.). Benchmarking commonly refers to a procedure of comparing the average performance of a particular industrial sector with the organization's own performance (Komonen, Kunttu and Ahonen, 2011). It helps in developing realistic goals and strategic targets, facilitates the achievement of excellence in operation and maintenance (Almdal, 1994), and enhances transparency and performance (Braadbaart, 2007). The benchmarking procedure may include qualitative and/or quantitative methods. Qualitative methods can provide detailed information and can be utilized if the number of companies involved is modest, whereas quantitative methods offer an efficient way to collect and analyze a large data set from a larger number of companies. Benchmarking can be used to identify improvement potential in SAM practices and it serves as an input for planning and prioritizing development actions (Kunttu, Kortelainen and Horn, 2017).

Maturity models

Maturity models have similarities with benchmarking methods and they can be used to benchmark strategies, characteristics and processes against other similar organizations. Asset-related maturity models are structured approaches that aim at describing SAM performance or the level of SAM capabilities. Understanding the maturity level of SAM helps organizations to develop their AM strategies. They are commonly used to evaluate the level and characteristics of AM and maintenance. Maturity models have been used, for instance, in managing organizational capabilities (Chemweno et al., 2015).

Komonen, Kortelainen and Räikkonen (2006; 2012) present a maturity model that categorizes asset strategies according to the dynamics of market and technology development. Technology dynamics refers to the competitiveness of the asset (stable and long-lifetime or dynamic and short lifetime of technology) and market dynamics refers to the demand trend for the product (dynamic or stable market). Van der Lei, Wijnia and Herder (2012) extend this work by presenting a framework for assessing the maturity of AM systems and strategies that includes asset characteristics, environment, life cycle and management dimensions. Asset characteristics include function (public or commercial), behavior (discrete, continuous or passive), life cycle length, location, and type (mechanical, civil, software, etc.). Environment covers market and technology development and life cycle the key life cycle phases. The management dimension focuses on people, KPIs, budgets, processes and systems.

Risk management approach

Risk management can be defined "as coordinated activities to direct and control an organization with regard to risk". A risk management process consists of "systematic application of policies, procedures and practices to the activities of communicating and consulting, establishing the context and assessing, treating, monitoring, reviewing, recording and reporting risk". (ISO 31000, 2018). Risk assessment includes risk identification, risk analysis and risk evaluation. There are several risk assessment methods available, including for example preliminary hazard analysis, hazard and operability study, failure modes and effects analysis, event tree analysis, bow tie analysis, Monte Carlo simulation and Bayesian statistics and nets (IEC, 2010).

Monetary assessment methods

Monetary assessment methods include commonly used decision support approaches, such as cost-benefit analysis (CBA), life cycle cost analysis (LCCA) and total cost of ownership (TCO). All of the methods are quantitative and require information on the costs and benefits of decision alternatives.

CBA can be defined as a comparison of the marginal costs of policies with the marginal benefits in order to identify the most economically-efficient decision alternative (Dessler and Parson, 2005). It provides monetary valuations for all impacts involved and is particularly suited to situations in which the future financial effects can be identified and predicted (Scrieciu et al., 2014). Issues in using CBA include difficulties in valuation of externalities (Scrieciu et al., 2014), and the inclusion of complex features such as future time, doubt, irreversibility and indirect benefits (Mediation, 2013; Verbruggen, 2013).

LCCA is a method for specifying the estimated total incremental costs of the development, production, usage and retirement of a particular item. LCCA is commonly used in decisions on system maintenance concepts and plans, equipment design configuration, procurement sources and the selection of a supplier for a given item, and product disposal and recycling methods (Asiedu and Gu, 1998). As most of the life cycle costs of an asset are committed during the design and development stage (Dowlatshahi, 1992), LCCA should be utilized at an early stage of design (Uusitalo et al., 2014). As a similar method to LCCA, TCO is aimed at understanding the true cost of buying a particular good or service (Ellram, 1995). TCO may include elements such as acquisition cost, transportation, inspection, replacement, downtime caused by failure, and disposal costs (Kortelainen et al., 2017b).

Multi-criteria decision analysis

Assessing SAM decisions often requires an approach that incorporates the perspectives of stakeholders in the problem and solution definition. In a complex decision-making situation involving multiple stakeholders, a decision maker may have several conflicting objectives. In multi-criteria decision analysis (MCDA) the consideration of quantitative and qualitative data together using multiple decision criteria is permitted (UNFCCC, 2010). The decision criteria should reflect what decision makers find important in decision situations (Molarius et al., 2008). Using the method, the benefits and costs are measured on a value scale that reflects the desirability of the alternatives from the perspective of the decision maker (Porthin et al., 2013). In the method, weights are given to each decision criterion and the weighted sum of the different criteria is taken in order to gain an overall score for the alternative. The result is used to rank alternatives. MCDA is appropriate when there are difficulties in assigning monetary value to the decision criteria (Mediation, 2013). MCDA is utilized in the management of infrastructure assets such as water and wastewater systems, bridges, transportation and buildings to integrate various technical information and stakeholder values (Kabir, Sadiq and Tesfamariam, 2014).

Participatory methods are often utilized to support different stages of the MCDA process, for example, to provide weights and valuations for criteria that are difficult to otherwise quantify. They cover a variety of approaches that support the inclusion of experts and users in the decision-making and assessment process. They are also utilized in understanding complexity, participatory analysis and stakeholder engagement and mapping. Participatory methods may, based on the joint work of scientists, experts and stakeholders, lead to better assessments because they combine the latest expert information with first-hand policy experience (Toth and Hizsnyik, 2008).

Robust decision-making and real options

The goal of robust decision-making (RDM) is to, first, identify the full range of plausible future states and, second, make decisions that are robust across as wide a range of such future states as possible (Scrieciu et al., 2014). RDM starts with selecting decision alternatives and then estimating the utilities of alternatives to identify the potential vulnerabilities of strategies (Mediation, 2013). Key elements of the method include: 1) assembling a high number of scenarios, 2) seeking strategies that perform sufficiently well across a broad range of scenarios, 3) employing adaptive strategies to achieve robustness, and 4) designing an analysis for interactive exploration of the plausible futures (Mediation, 2013). RDM is a complex method that requires advanced statistical and mathematical models, which can be seen as a challenge in utilizing the method (Scrieciu et al., 2014).

Real options are suitable for situations where precise costs and benefits become clear as implementation proceeds. The value of options that are opened up during the implementation of the selected project are hard to capture using traditional methods. Real options are choices of direction at particular points in time during strategy implementation. They add strategic flexibility that can be used for expanding, extending or closing down a project. Benefits of real options include clearer understanding of the strategic and financial risk of strategies by examining each option separately, enabling valuation of emerging options, and coping with uncertainty. (Johnson, Scholes and Whittington, 2008)

Scenario analysis

Real options can be linked to methods for analyzing uncertain futures, such as scenario analysis (Johnson, Scholes and Whittington, 2008). In addition, methods such as MCDA and RDM utilize scenario analysis. Scenario analysis explores systematically how the future could evolve from the past and present, i.e. alternative future states (Van der Heijden, 1996; Refsgaard et al., 2007). Scenario analysis can be useful for evaluating weak signals and challenging rooted beliefs (Andersen and Schrøder, 2010). Typical scenario types include qualitative, quantitative, baseline, and policy (Alcamo, 2001; Refsgaard et al., 2007). For SAM, qualitative scenarios are the most common alternatives due to insufficient data and restrictive assumptions involved in quantitative scenarios (Andersen and Schrøder, 2010).

Advanced analytics methods

With the emergence of IoT and industrial internet, vast amounts of data have been created. Therefore, there is a huge demand for more efficient ways of utilizing the data (Da Xue et al., 2014). The most common industrial applications for data analytics are related to condition-monitoring, machine prognostics and reliability issues. However, decisions regarding SAM can also be supported by advanced analytics methods. Analytics methods can generally be divided into descriptive, diagnostic, predictive and prescriptive analytics (e.g., Gartner, 2012). Descriptive and diagnostic analytics are focused on past events, whereas predictive and prescriptive analytics are forward-looking methods. Artificial intelligence, or more precisely machine learning, is often referred to as a potential approach for decision support. Techniques such as artificial neural networks (ANN), genetic algorithms (GA), and support vector machines (SVM) are mentioned as potential for supporting SAM (Shafiee et al., 2019).

3. Methodology

This chapter discusses the philosophical and methodological foundation of the research. It presents the methodological choices that were made during this dissertation process.

Before discussing the methodological foundations of the research, the philosophical underpinnings of the research should be understood. Saunders, Lewis and Thornhill (2016) define philosophy of science as "a system of beliefs and assumptions about the world and the development of knowledge." The philosophical framework of research is built on ontology, epistemology and axiology (ibid.). Ontology refers to the study of existence: it explores the nature of the researched phenomenon (Hirsjärvi, Remes and Sajavaara, 2014). Two aspects of ontology are objectivism and subjectivism. Objectivism argues that social entities exist in reality external to actors concerned with their existence. Instead, subjectivism argues that social phenomena are created from the perceptions and actions of actors concerned with their existence (Saunders, Lewis and Thornhill, 2016).

Epistemology discusses the sources of knowledge and what is the best method or approach for the research. It concerns what is acceptable knowledge in a field of study (Saunders, Lewis and Thornhill, 2016). Together, ontology and epistemology form the basis for the selection of theory, terminology and concrete research design. Axiology is another key philosophical context. It refers to assumptions on how the researcher's own values influence the research (ibid.). Figure 4 presents the philosophical and methodological choices and foundations that a researcher should consider.

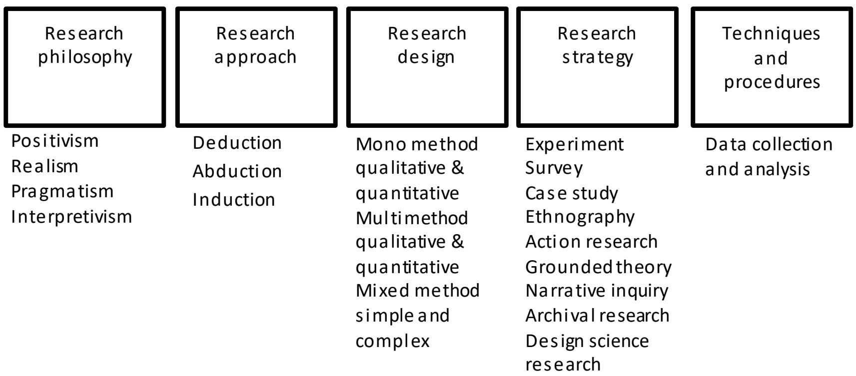


Figure 4. Philosophical and methodological foundations of research. Adapted from Saunders, Lewis and Thornhill (2016).

3.1 Research philosophy

Four main types of research philosophies can be identified: positivism, realism, interpretivism and pragmatism (Table 4). Positivistic and interpretative are the two main ways of doing research (Koskinen, Alasuutari and Peltonen, 2005).

Table 4. Comparison of research philosophies in management research (adapted from Vaishnavi and Kuechler, 2004; Koskinen, Alasuutari and Peltonen, 2005; Creswell, 2014; Saunders, Lewis and Thornhill, 2016).

	Positivism	Realism	Interpretivism	Pragmatism

Ontology	External and objective	Objective. Realist: independent of human thoughts or beliefs Critical realist: independent of human thoughts or beliefs but interpreted through social conditioning	Subjective	External, multiple, researcher's view depends on research question
Epistemology	Observable phenomena provide credible data. Causality and generalizations in focus	Observable phenomena provide credible data Direct realist: insufficient data means inaccuracies in sensations Critical realist: phenomena create sensations that are open to misinterpretation	Subjective meanings and social phenomena in focus	Observable phenomena and subjective meanings can provide acceptable knowledge (dependent on research question). Focus on practical applied research that integrates different perspectives
Axiology	Value-free, objective research	Research is biased by world views, cultural experiences that will impact on the research	Researcher is part of what is being researched and cannot be separated	Values have a large role in interpreting results, the researcher adopts both objective and subjective points of view
Data collection techniques	Highly structured, large samples, quantitative, but can also use qualitative techniques	Methods should fit the subject, quantitative or qualitative	Small samples, in-depth investigations, qualitative	Mixed or multiple method, quantitative and qualitative

The positivistic research philosophy usually adopts a stance of the natural scientist (Saunders, Lewis and Thornhill, 2016). The research question is derived from scientific literature and modified into a hypothesis which is tested empirically (Koskinen, Alasuutari and Peltonen, 2005). Research is undertaken value-free; the researcher is independent of the subject of research, i.e. does not affect, and is not affected by, the subject of research (Remenyi et al., 1998). The positivistic researcher commonly uses a highly structured methodology to facilitate replication and the emphasis is on quantification (Saunders, Lewis and Thornhill, 2016).

In contrast to positivistic philosophy, interpretivism argues that rich insights into the complex world are lost if the complexity is reduced to law-like generalizations. In interpretative research it is necessary to understand differences between humans in our role as social actors. Adopting an interpretative philosophy, the researcher enters the social world of the research subjects to try to understand the world from their point of view.

Realism as a philosophical position argues that there is a reality that is quite independent of human mind. Objects have an existence independent of mind. From the epistemological perspective realism is similar to positivism in the sense that it assumes a scientific approach to the development of knowledge. There are two forms of realism: direct and critical. In direct realism, what is experienced through our senses portrays the world accurately. In contrast, critical realism argues that that we experience images of real-world things, not the things directly. (Saunders, Lewis and Thornhill, 2016)

This research follows the research philosophy of pragmatism. When following a pragmatist research philosophy the most important consideration is the research question. The research question is the most important determinant of the epistemology, ontology and axiology that are adopted (Saunders, Lewis and Thornhill, 2016). Use of mixed methods (qualitative and quantitative) according to their research purposes is an appropriate approach in pragmatist research philosophy (Creswell, 2014).

The rationale behind the selection of pragmatism as the research philosophy is that design science research (DSR) is used as the research strategy. DSR is claimed to follow the philosophy of pragmatism (Vaishnavi and Kuechler, 2004). In DSR, ontological and epistemological viewpoints may shift as the research progresses through the design science research cycle: reality may be created through constructive intervention (interpretative) and the behavior of system then assessed as a positivist observer (ibid.). Gregg, Kulkarni and Vinzé (2001) and Vaishnavi and Kuechler (2004) present the philosophical assumptions of DSR. From the ontological perspective, there are multiple alternative world-states. Stable, underlying, physical reality constrains these world-states. From the epistemological stance, the process of iterative development reveals what information means. Thus, from the epistemological perspective, DSR adopts a pragmatist view. From the axiological point of view, control of environment, creation and progress are valued over truth or understanding. However, in the context of this study, truth and understanding are also relevant.

3.2 Research approach

Selecting a research approach enables the researcher to make more informed decisions about the research design and strategy including, for instance, what kind of evidence is gathered and how it is interpreted (Easterby-Smith et al., 2013). There are three research approaches: inductive, deductive and abductive. The deductive approach is about testing theory through formulating and testing hypotheses, inductive is about creating new theory based on data, and abductive is about iteratively creating and testing the "best possible" explanation of the research problem identified at the start of the study.

In the deductive approach, a theory and hypothesis are developed and a research strategy is designed to test the hypothesis. The goal is either to falsify or verify a theory. Key characteristics of the deductive approach include explaining causal relationships between variables, controls to allow the testing of hypotheses, structured methodology to facilitate replication, operationalizing of concepts to allow quantitative measurement, reductionism, and reasoning from general to specific. (Saunders, Lewis and Thornhill, 2016)

In the inductive approach, data is collected and a theory is developed based on analysis of the data. The methodology in inductive research is often less rigid than in deductive research and enables alternative explanations of the phenomenon. In contrast to the deductive approach, generalization of results is from specific to general. A small sample size is often appropriate, because the inductive approach is concerned with the context in which events are taking place. Data is utilized to explore phenomena, identify themes and create conceptual frameworks. (ibid.). An inductive approach may be appropriate when the topic is new and there is little existing literature (Creswell, 2014).

In the abductive approach, the starting point is surprising facts or puzzles and the research process is devoted to their explanation (Bryman and Bell, 2015). The goal is to either generate new theory, modify existing theory, or apply existing theory in new ways. Generalization of results is derived from interactions between specific and general. Data is utilized similarly to the inductive approach to identify themes, explore phenomena and create conceptual frameworks that are tested through additional data collection. (Saunders, Lewis and Thornhill, 2016).

Combining research approaches is often advantageous (ibid.). Developing decision support methods through DSR gives guidelines for selecting a research approach for the different stages of research. Understanding the research problem may be abductive, deriving design propositions deductive, evaluation inductive or deductive, and confirming theoretical contributions inductive (Vaishnavi and Kuechler, 2004; Lukka, 2006; Fischer and Gregor, 2011). In the first phase of this research, an inductive approach is utilized to collect emerging trends and perspectives in SAM and existing methods for supporting SAM. An abductive research approach is then used in the development of initial decision support methods. The methods are then evaluated using inductive case studies and deductive comparison to existing literature. Finally, an inductive approach is employed in the conclusion phase of the research to confirm the theoretical and managerial contributions.

3.3 Research design

The research design serves as an action plan by which the researcher moves from research questions to conclusions (Koskinen, Alasuutari and Peltonen, 2005). It consists of research strategies, research choices and time horizons (Saunders, Lewis and Thornhill, 2016). Based on time horizon, research can be divided into cross-sectional or longitudinal. Cross-sectional research focuses on a particular phenomenon at a particular time, i.e. “a snapshot taken at a particular time.” Longitudinal research observes a phenomenon over a longer period of time, i.e. “diary” (Saunders, Lewis and Thornhill, 2016).

The research design specifies how and from where research data is gathered and describes the logic that links the data to principles for the interpretation of the results (Koskinen, Alasuutari and Peltonen, 2005). Research designs can be categorized as qualitative, quantitative and mixed method approaches (Creswell, 2014; Saunders, Lewis and Thornhill, 2016). Research questions guide the selection of the research design in this dissertation, which is in line with the pragmatist research philosophy. Therefore, the focus is mainly on qualitative research. Qualitative research is selected because the research aims to achieve a holistic perspective of the research object. In addition, it enables the exploration of alternative methods and enables in-depth analysis of a small number of cases. Table 5 presents the research design in this dissertation.

Table 5. Research design in this dissertation.

Publication / Outcome	Goal of research	Time horizon	Research approach	Research strategy
1	Derive guidelines for strategic asset information management Create understanding about the status of strategic asset information management and sustainability	Cross-sectional	Deductive	Qualitative case study. Case: three Finnish companies in asset-intensive industry
2	Create understanding about existing frameworks that support SAM and what kind of perspectives and trends they cover	Cross-sectional	Inductive	Systematic literature review

3	Create and test a method and assess the effects circular economy on asset management	Longitudinal	Combination of inductive, deductive and abductive	Design science research
4	Create and test a method for supporting SAM in the water and sewage sector	Longitudinal	Combination of inductive, deductive and abductive	Design science research
5	Create and test a method for supporting decision-making in complex and uncertain decision contexts (schematic examples and case renewable energy)	Longitudinal	Combination of inductive, deductive and abductive	Design science research
6	Create and test a method for supporting decision-making in complex and uncertain decision contexts (case drought and heatwave and nuclear energy)	Longitudinal	Combination of inductive, deductive and abductive	Design science research

The main research strategy in this dissertation is design science research, which is utilized in publications 3-6. In P1 and P2, the research strategies are qualitative case study and systematic literature review, respectively. However, the as the role of the research strategies in P1 and 2 is to support the early phases of DSR, they are described as a part of the DSR process in the next chapter.

3.4 Research strategy: design science research

The main research strategy in this dissertation is design science research (DSR) (e.g. Simon, 1997; Hevner et al., 2004). DSR has similarities with the constructive research approach (Kasanen, E., Lukka, K. and Siitonen, 1993; Lukka, 2006). The constructive research approach involves solving problems through constructing models, diagrams, plans and organizations (Kasanen, E., Lukka, K. and Siitonen, 1993), whereas DSR creates and evaluates artifacts intended to solve identified organizational problems in the real business environment (Hevner et al., 2004). Artifacts include constructs, models, methods or instantiations (March and Smith, 1995), such as decision support systems (Muntermann, 2009) and information system planning methods (Peffers et al., 2007). DSR has been used in information systems field and management research (Piirainen and Gonzalez, 2013). It addresses important unsolved problems in innovative ways or solved problems in a more effective or efficient way (Hevner et al., 2004). The design and theoretical science approaches are highly complementary as design science creates artefacts for theoretical science to evaluate (Holmström, Ketokivi and Hameri, 2009).

DSR addresses wicked problems (Hevner et al., 2004) that are characterized by unstable requirements and constraints derived from ill-defined environmental contexts, complex interactions between the problem and its solution, malleable processes and artifacts, and the need for teamwork and creativity to produce effective solutions. Developing methods for SAM involves, for instance, complex interactions between problem and solution and requires teamwork and creativity to produce effective solutions. The stages, iterative cycles, and research approaches in this dissertation are presented in Figure 5.

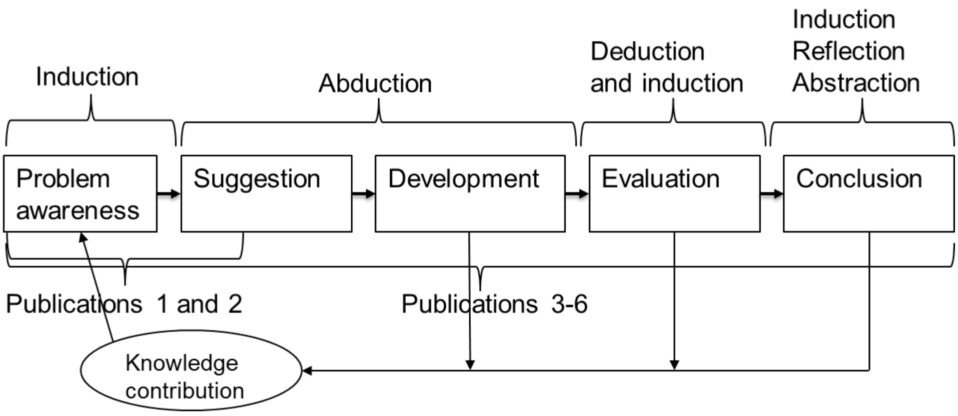


Figure 5. Design science research cycle in this dissertation. Adapted from Vaishnavi and Kuechler (2004), Fischer and Gregor (2011) and Piirainen and Gonzalez (2013)

The first phase of DSR involves developing awareness of the problem and proposing a definition of it (Vaishnavi and Kuechler, 2004). Interviews and literature research were the main activities in this phase. This phase may include activities such as identifying interesting goals and situations and scanning parallel knowledge domains (Holmström, Ketokivi and Hameri, 2009). A case study approach and systematic literature review are utilized in developing problem awareness. Case study is one of the most common research methods in qualitative business research. In case study research, rich and intensive information is collected from a single case or a small group of interconnected cases that are selected carefully (Hirsjärvi, Remes and Sajavaara, 2014). These serve as a source of new ideas and hypotheses and can be utilized to test established concepts and theories (Koskinen, Alasuutari and Peltonen, 2005). The case study approach was utilized in P 1, 3, 5 and 6. Systematic literature review is a replicable, scientific, and transparent process that aims to minimize bias through exhaustive literature searches. The method should provide an audit trail of the researcher’s decisions, procedures, and conclusions (Cook et al., 1997; Tranfield, Denyer and Smart, 2003). A systematic literature review was utilized in P2. The output of this phase is a proposal for new research (Vaishnavi and Kuechler, 2004).

During the second phase, solutions are identified and a tentative design is formed (Holmström, Ketokivi and Hameri, 2009; Piirainen and Gonzalez, 2013). This phase is intimately linked with the first phase. Human creativity is required in the transition from proposal to tentative design, in which new functionality is envisioned based on a novel mix of either existing or new and existing elements (Vaishnavi and Kuechler, 2004). The systematic literature review and case study research strategies also supported this phase.

In the third phase, partial solution artifacts are built, tested and developed (Vaishnavi and Kuechler, 2004; Piirainen and Gonzalez, 2013). The tentative design is refined and there is iteration between solution designs, implementation and evaluation (Holmström, Ketokivi and Hameri, 2009).

The fourth phase consists of evaluating the performance of alternative artifacts and possible design iterations (Vaishnavi and Kuechler, 2004; Piirainen and Gonzalez, 2013). Artifacts are evaluated according to criteria that were set in the first phase. Often, artifacts are evaluated based on their utility and/or fitness to adapt and survive within an environment (Hevner et al., 2004; Gill and Hevner, 2013). The results of this phase and information gained in the construction and testing of the artifact are brought together to further develop the design (Vaishnavi and Kuechler, 2004). In this study, the case study approach was utilized to build, develop, test and evaluate the artifacts, i.e. decision support methods.

The fifth phase involves drawing conclusions and communicating results. At the start of this phase, the research effort (decision support method) is deemed "good enough." It includes activities such as theoretical reflection on the solution design and linking the solution design to the theoretical discourse (Holmström, Ketokivi and Hameri, 2009). Communication is a crucial part of DSR (see Knowledge contribution in Figure 5) (Hevner et al., 2004).

Table 6 presents the role of DSR in developing, testing, evaluating and communicating the results of the developed methods and frameworks.

Table 6. Role of DSR in methods

Method	Problem awareness and proposal	Finding solutions and tentative design	Building and testing artifact	Evaluating and iterating	Communicating results
Main research question / subquestions	SQ1: What are the emerging trends and perspectives affecting strategic asset management in modern organizations?	SQ2: What methods exist for supporting the strategic asset management of organizations?	SQ3: What strategic asset management decision support methods can be developed for managing assets in complex and uncertain decision contexts?	SQ4: How can the developed strategic asset management support methods be tested in practice?	MRQ: How to manage assets in complex and uncertain decision contexts with strategic decision support methods?
Method 1: (P3) Method for assessing and developing circular economy solutions from the perspective of asset management	Familiarizing with circular economy and AM literature. Interviews with industry experts. Identifying a research gap in the role of AM in circular economy solutions	Utilizing existing classifications and analysis frameworks: AM fundamentals (ISO 55000-2, 2014) and circular economy models (Bocken et al., 2016; Lacy and Rutqvist, 2016) for initial solution	Finding existing examples of circular economy solutions and positioning them to the circular economy framework. Assessing them through the lenses of AM fundamentals to identify their opportunities and threats	Evaluating and further developing the framework based on the data from two workshops	Presenting the results for industry experts and researchers in a scientific conference (MPMM2016). The method is linked to the emerging theoretical discussion of AM and circular economy
Method 2: (P4) Strategic asset management frameworks for water and sewage sector decision-making	Familiarizing with water and sewage sector and asset management literature. Interviews with industry experts and stakeholders. Identifying a	Identifying relevant decision criteria from the literature and based on the interviews. Identifying existing methods for supporting SAM decisions in the water and	Creation of variables for indicating the value of the water system and how they address the identified needs of the stakeholders. Identification of potential sources of information for	Evaluating the model based on feedback received from water sector experts in a workshop	Presenting the results to industry experts and researchers in a scientific conference (CESUN2012) and in a journal. The method is linked to the theoretical discussion of AM

	lack of holistic view for the management of water and sewage sector assets.	sewage sector and other sectors	these indicators and illustrating the solution with a simple checklist		in the water and sewage sector
Method 3: (P5 and P6) SRVM (Strategy Robustness Visualization Method)	Familiarizing with decision support and CC adaptation literature. Interviews with industry experts, stakeholders and researchers. Identifying a need for method for incorporating climate change adaptation to SAM	Identifying methods for supporting climate change adaptation decisions. Identifying and committing stakeholders to the process	Developing the SRVM method. Identifying relevant case themes and building case studies. Creating decision criteria, adaptation strategies and scenarios	Evaluating the method based on data from four workshops with stakeholders and researchers. Testing the method by presenting two case studies	Demonstrating the method and cases in a session as part of European Climate Change Adaptation conference (ECCA2015) with 5 stakeholders participating and an audience of 15 researchers and industry experts and for experts at European Commission in Brussels. The method is linked to the theoretical discussion of supporting climate change adaptation related decision-making

3.5 Data collection and analysis

Data collection and analysis in the publications is presented in Table 7.

Table 7. Data collection and analysis in publications

Publication	Data collection methods	Data	Data analysis methods
1	Semi-structured interviews	Six semi-structured interviews involving 14 persons with three Finnish companies operating in asset-intensive industries. The interviews were recorded and transcribed	Qualitative analysis: Content analysis and deductive approach
2	Systematic literature review	37 methods for supporting strategic asset management identified in the literature review	Qualitative analysis: Inductive approach
3	Literature research, semi-structured interviews, expert workshops	5 identified CE models from the literature, 5 examples of CE solutions, 25 semi-structured individual and group interviews with industry experts, data from two expert workshops with 4 researchers for analyzing the impacts of CE models on AM and developing the method	Qualitative analysis: Inductive approach in analyzing the interviews DSR in developing the method
4	Semi-structured interviews, literature research, informal interviews and expert workshops	15 semi-structured interviews with water supply network specialists in several companies and municipalities, literature research on municipal reports and scientific publications, informal interviews and an expert workshop with water	Qualitative analysis: Inductive approach in analyzing the interviews DSR in developing the method

		utility experts, service providers and researchers to develop the method	
5	Semi-structured interviews, literature research, expert workshops, data from modelling	15 semi-structured interviews to gain background information on the climate change impacts and adaptation; 5 workshops with a governmental decision-maker, an energy industry representative, representatives from an energy company, electricity network specialists and researchers when developing the method and to gain expert opinions on the case study; modelling results from TIMES and Balmorel models	Qualitative analysis: Inductive approach in analyzing the interviews DSR in developing the method
6	Semi-structured interviews, expert workshops, data from modelling	3 semi-structured interviews with representatives from energy companies and electricity network specialists to gain expert opinion and background information for the case study, two expert workshops with researchers to develop the case study, modelling results from ARIO model	Qualitative analysis: Deductive approach in analyzing the interviews DSR in developing the method

The main data collection methods in this study were semi-structured interviews, systematic literature review and literature research, and expert workshops. In addition, results from modelling were utilized in publications 5 and 6. These data collection methods were suitable for DSR.

Using interviews, the researcher can test their interpretations with specialists and identify false interpretations. The challenge of interviews is that they offer indirect information. Semi-structured interviews allow more freedom to the interviewee compared to structured interviews. Although questions are thought out beforehand, the interviewee may answer them freely and also suggest new questions. (Koskinen, Alasuutari and Peltonen, 2005). In this dissertation, the interviews were the main research data (P1), brought background information on the research topics (P 3-6), and provided expert opinion based information on the performance of AM strategies (P6).

Content analysis was used in analyzing the data in P1. A deductive approach to qualitative analysis was utilized as the analyzed data was benchmarked against the guidelines presented in ISO 55000-2 (2014). A deductive approach was also utilized in analyzing the interviews in P6. In the deductive approach, the theoretical framework formulated by the researcher guides the data analysis (Yin, 2003). The inductive approach to qualitative analysis was utilized in analyzing the results of interviews (P 2-5). In the inductive approach data is collected and explored to identify the themes or issues to follow up and focus on (e.g. Yin, 2003). In this approach the researcher needs to analyze the data as it is collected and develop a conceptual framework to guide the subsequent work (Saunders, Lewis and Thornhill, 2016).

Literature research was executed mainly to identify the state of the art of SAM and methods supporting SAM decisions. An inductive approach to qualitative analysis was utilized in analyzing the results of the literature research (P 2-5). Systematic literature review was utilized for data collection and analysis (P2) and was selected as a research strategy to collect data on the characteristics of decision support methods for SAM and emerging trends and perspectives affecting SAM. In P2 an iterative process modified from method presented in Tranfield, Denyer and Smart (2003) was utilized consisting of data collection, descriptive analysis and category selection, and data evaluation.

Three types of expert workshop were conducted. The first of these focused on developing and testing the decision support methods in the workshop setting with researchers and in some cases experts from business and the public sector (P 3-6). The second focused on eliciting performance scores and priorities for AM strategies and ranking of decision alternatives (P5 and P6). The third type focused on evaluating the decision support methods and demonstrating and communicating them to an extended audience (P 4-6). Extensive memos were prepared that summed up the results of the workshops.

The Balmorel, TIMES and ARIO models provided data for the two case studies in which SRVM was applied (P5 and P6). The models, data and analysis are not within the scope of this study, however, they are explained in detail in P5 and P6 and in Hanski, Rosqvist and Crawford-Brown (2015).

3.6 Quality of the research and limitations

The quality of research is usually assessed according to the reliability and validity of its results (Saunders, Lewis and Thornhill, 2016). Validity refers here to how much a claim, interpretation or result is about what it appears to be about i.e. is there a causal relationship between the variables. There are two classes of validity; internal and external. Internal validity explains the level of internal logic and contradiction of the interpretation. External validity addresses how well the interpretation can be generalized. Other types of validity, such as the validity of a construct, are also sometimes differentiated.

In terms of case study research, generalization of the results may be problematic. Especially in the case of a single case study the aspect of generalization should be considered. A small number of cases may be used as a basis for broad generalizations only in special cases. However, generalization from a single case is possible with a help of supporting theory (Yin, 2003). In this dissertation, a small number of case studies complemented the DSR process. Selective sampling was used to choose the cases for the research (Coyne, 1997). In addition, the case studies were connected to the supporting theoretical background. In addition, the case studies used for testing the Method 3 (Strategy Robustness Visualization Method, see table 6) were highly detailed. The small number of cases is, however, considered a limitation for the generalization of results in this dissertation. Further research and additional case studies are needed to validate the methods.

In evaluating research, four types of triangulation are identified: 1) data, 2) investigator, 3) theory, and 4) methodological triangulation (Patton, 1987). Several data sources should always be used when conducting case research. Using several sources enables the research of several factors and increases the validity of the construct (Yin, 2003). In this dissertation, data triangulation, i.e. several data sources such as interviews, literature research and workshops, was utilized. The chain of reasoning should be made possible to follow for readers (Yin, 2003). In this research, the chain of reasoning and research process were clarified by Figures 2, 3 and 6. Methodological triangulation (Patton, 1987), i.e. using multiple complementary research methods, can be utilized to improve the validity of results. In this dissertation, DSR was complemented by systematic literature review and case study research.

Reliability refers to the consistency with which cases are located in the same classes by different observers at different times. Reliability has four characteristics: congruence (how different indicators measure the same object), accuracy of the instrument, objectivity of the instrument (how well the observer is understood by others) and continuity of the phenomenon (the uniqueness vs. continuity of the phenomenon) (Koskinen, Alasuutari and Peltonen, 2005). The reliability of the present research is increased by investigator triangulation (Patton, 1987) involving several researchers and stakeholders in the research and constructing and testing the methods using the DSR research strategy.

As the main research strategy in this dissertation is DSR, the quality of DSR was in focus. Hevner et al. (2004) presents guidelines for DSR. These guidelines and how they are met in this dissertation (*in italics)* are presented in Table 8.

Table 8. Design science research guidelines and how they are met in this dissertation (Adapted from Hevner et al., 2004)

Guideline	Description
Design as an artifact	Design science research should produce a viable artifact → *Decision support methods for SAM have been created (artifact) and tested and evaluated during the development process*
Problem relevance	Objective of research is to develop solutions to important and relevant business problems → *The methods address the identified need for supporting SAM decisions in complex and uncertain decision contexts. Need for considering emergent trends and perspectives is also identified in the literature*
Design evaluation	Utility, quality and efficacy of artifact should be demonstrated rigorously via evaluation methods → *The methods were evaluated during the development process by workshops, interviews and case studies (observational evaluation). The methods are connected to the existing literature and scenarios are utilized in P5 and P6 (descriptive evaluation)*
Research contributions	Research must provide clear and verifiable contributions related to the artifact, design foundations and/or design methodologies → *Research provides new methods for supporting SAM (artifacts, design methodologies) and novel theory related to SAM and its key emerging trends and perspectives (design foundations)*
Research rigor	Methods in construction and evaluation of artifact should be rigorous → *The process of data collection, constructing and evaluating the methods is described. Rigor is ensured by constructing the methods in cooperation with experts and stakeholders. It should be noted that overemphasis on rigor may lower the relevance of DSR (Hevner et al., 2004)*
Design as a research process	"Search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment" → *The methods were developed iteratively by generating alternative designs and testing them against requirements (e.g. utility). Satisficing methods (Simon, 1997), i.e. methods that are satisfactory, were created*
Communication of research	Research should be presented effectively to technology and management oriented audiences → *Technological details of the research are presented in publications and other described background material. Managerial contributions of the research are described in chapter 5.3*

To summarize this chapter, the methodological basis of this dissertation was presented. DSR was introduced as the main research strategy. DSR was complemented with a systematic literature review and case study research. Qualitative data collection and analysis methods were utilized. In this dissertation, many actions have been undertaken in order to ensure the validity and reliability of the research, including data, investigator and methodological triangulation and adherence to the guidelines presented in Hevner et al. (2004).

4. Summary of publications

The following publications provide different perspectives on SAM. P1 focuses on the state of the art from the perspective of information asset management. P2 presents an overview of methods available for SAM and their characteristics. P 3-6 present methods for supporting SAM and crucial perspectives and trends affecting SAM.

4.1 Publication 1: Strategic asset information management: experiences from Finnish companies

Motivation

AM decision-making has been based more on intuition and visions rather than structured and well-tooled analysis (Komonen, Kortelainen and Räikkönen, 2012). ISO 55000-2 (2014) gives guidelines for improving AM strategies and practices, creating and developing a sustainable SAM system, and asset information management. To improve these strategies and practices, there is a need for more information on their current level in companies. Three companies were interviewed about their SAM, especially related to their asset information management practices and sustainability. The results were compared with the guidelines given in ISO 55000-2 (2014). Table 9 presents the guidelines against which the practices identified in the companies were analyzed.

Table 9. Guidelines for information asset management (adapted from ISO 55000-2, 2014).

Asset management activity	Guidelines
Asset management strategies and sustainability	• Environmental, economic and social pillars of sustainability and the fulfilment of sustainability-based organizational objectives are emphasized • The role of stakeholders and their requirements and expectations are highlighted • Stakeholders may have conflicting objectives for AM from the sustainability perspective. Thus, the AM system should be transparent and consistent • Organization should create a strategic AM plan that is consistent with organizational objectives. This plan is based on the characteristics and operational environment of the organization and sets criteria for AM decision-making
Collecting asset management related information	• Requirements and the necessary information items are set for the information needs and the documentation of information: user requirements, descriptions of assets and their purpose, various asset attributes, performance targets, key performance indicators, details of historical asset failures, etc. • Information needs of the organization should be determined through a formalized approach to meet its organizational objectives • Value and quality of information should be taken into account relative to its costs and complexity of collecting, processing and managing • Availability of appropriate AM-related information to assist in decision-making should be determined • Processes for collecting and managing asset information should be defined to ensure the accuracy, efficiency, traceability, auditability and timeliness of business processes and reporting • Methods for the measurement and collection of source information, the frequency and verification of its measurement, and its storage and approval for further analysis should be defined
Analysis and utilization of asset information	• Organization should define, implement and maintain the methods for analysis and evaluation of information, and processes for managing its information • There are differing information needs at different levels of the organization and differing abilities to achieve horizontal and vertical alignment of information • Organization should consider the complexity of its processes for managing its asset information

	• Asset-related data can reside in many systems and, thus be very expensive to gather and maintain. Unnecessary duplication of data should be avoided and the data should reside in the most appropriate system • Processes for where and how the data is reworked into usable information and how it will be communicated should be defined
Asset management risks, information exchange, and the quality and availability of information	• Organization should consider the significance of the identified risks; exchange of information with its stakeholders, including service providers; and the impact of quality, availability and management of information on organizational decision making. • Organization should consider the need to align its information requirements to suit the level of risk that an asset poses. • The information should be easily exchangeable with service providers. • Use of common terminology increases understanding between stakeholders and inside the organization. • To ensure the completeness, accuracy and integrity of AM information, collaboration amongst relevant stakeholders is needed. • There is a need for a quality of information that is relative to its use.

Results

A number of SAM developments that increase sustainability were undertaken by the companies under study. However, their AM strategies were not necessarily based on sustainable thinking, even though they may have increased the sustainability of the company. The companies' primary motivation is for process development and energy and resource efficiencies that provide cost savings or increased capacity.

No formalized approach to determining information needs was identified, although, due to the limited number of interviews, it cannot be ruled out that formalized approaches for determining information needs might be in place. The value and quality of information are taken into account. All of the companies collect data from their assets and use it to support AM-related decision-making. The companies have methods and processes for collecting and managing asset information, i.e. customer feedback questionnaires and availability and quality criteria.

The companies analyze the information collected from machinery and infrastructure. Purely statistical analysis is thought to be inadequate in an industrial setting and is therefore often complemented with condition-based information on assets. There is a need for methods for the evaluation of information. Different information needs at different levels of organization have been recognized and examples of alignment have been identified. Even though a lot of information is produced, the state of critical components may not always be provided. The companies have recognized the need for unified systems and the expensiveness of duplicating the data in several information systems. Additionally, actions have been taken towards better asset data management.

The companies have processes for risk management in place and the significance of the risks is considered. There has been a shift from reactive actions based on analyses to predicting risks and carrying out predictive actions. Managers make predictions about machine failures at the operational level. On the tactical and strategic levels there are deficiencies in assessing the significance of risks and predicting machinery and infrastructure failures. Local risk assessments are made at facility level to determine the critical components. Exchange of information is mainly with customers. There is considerable variance in information exchange with the most prominent stakeholders depending on the existence of remote service systems or confidentiality issues. The companies gather data on their stakeholders through feedback, customer surveys and events. The impact of quality, availability and management of information on organizational decision-making is considered. In addition, the uncertainty of information is addressed and risk charts are used.

4.2 Publication 2: Sustainability in strategic asset management frameworks: A systematic literature review

Motivation

SAM plays a crucial role in improving the sustainability of companies. Companies should manage the sustainability impacts of their decisions on various stakeholders. Expressing sustainability in clear and concrete operational terms, linking important business processes to sustainability, and addressing the importance of AM in achieving sustainability have been challenging tasks. Varying types of assets and long lifetimes and sustainability requirements call for SAM frameworks for managing these assets. SAM frameworks should holistically consider different perspectives and emerging trends; however, limited information is available on the various perspectives and indicators that they should cover. Publication 2 gives guidelines for the development of more holistic SAM frameworks.

Results

Using a systematic literature review, existing SAM frameworks were identified and analyzed based on their type, application area, decision level, uncertainty management practices, and SAM indicators (Table 10).

Table 10. Characteristics of the identified SAM methods and frameworks.

Type of SAM framework	Application area	Decision level	Uncertainty management practices	SAM indicator groups
Guidelines and KPIs	Infrastructure	Purely strategic	Continuous improvement and assessment phase	Operational and technical
Asset maturity model	Manufacturing	Strategic and operative	Risk assessment methodologies, monitoring opportunities and risks	Regulation and external stakeholders
Other strategic maintenance or AM frameworks	General AM		Multi-criteria decision analysis methods, including sensitivity analysis and weighting methods	Organizational factors and quality of processes and systems
			Portfolio management	Financial
			Real options	Environmental
			Serious gaming	Social
			Scenario analysis	Strategic management
			Decision criteria, such as risk, uncertainty, volatility, and flexibility	Data and information management
				Technology
				Market and competition

Perspectives and trends such as strategy, policy, social governance, stakeholder and sustainability management, and climate change adaptation are neglected in SAM frameworks, whereas operational and technical perspectives are emphasized (Laue et al., 2014; Mahmood et al., 2015). The findings of the literature review largely align with these statements; however, some indicators representing the former perspectives were also identified. SAM frameworks include a large amount of indicators that can be divided into ten indicator groups. The indicator groups were situated in the external environment, in strategic management at the corporate level and in SAM contexts. In general, least attention was paid to indicator groups such as technology, market, competition, and information management.

SAM addresses the sustainability principles presented by Epstein and Roy (2003) and Epstein (2008), such as governance, transparency and protection of the environment. Governance is supported by enabling the effective management of an organization's resources. SAM allows process and product use data to be collected and utilized, which enables an increase in the performance of an organization's operations, products and services and in transparency to its community and stakeholders. Consequently, the life cycle of assets can be extended. Additionally, due to extended life cycles, increased availability of data and improved performance, SAM supports the protection of the environment by enabling a decrease in emissions and the consumption of materials and energy and an increase in the share of reusable materials.

4.3 Publication 3: Circular economy models – opportunities and threats for asset management

Motivation

Long-term sustainability and ecological footprint are being increasingly focused on by organizations and CE offers a step towards more sustainable business. However, adoption of CE business models has been low (Sommer, 2012; Linder and Williander, 2017). Companies have started to exploit the untapped potential of CE throughout their value chains and to promote resource and energy management concepts. Major global companies have been recently paying attention to CE; however, this should also be of key interest to SME companies, which are being increasingly affected by the shift to CE (Lewandowski, 2016).

The shift of companies toward CE implies radical changes not only in their business models but also in the ensemble of their supply chains, partnerships and value networks. On one hand, CE has implications for SAM practices. It creates opportunities and threats and enables new AM-related innovations. On the other hand, SAM has a major role to play in reaching the social, environmental and economic targets set for CE. However, there is a lack of methods for considering SAM perspectives in CE solutions (Korse et al., 2016). Therefore, there is a need for methods for investigating the effects of CE solutions on SAM, identifying their strengths and weaknesses, and developing them from the SAM perspective.

Results

Five general archetypes of CE solutions are identified: Circular supply-chain, recovery and recycling, product life extension, sharing platform, and product as a service (Bocken et al., 2016; Lacy and Rutqvist, 2016). The impact of CE on SAM can be discussed through four AM fundamentals. These include value that is provided to the organization, alignment of plans and activities, leadership and culture that ensures that employees in the organization have clear roles and responsibilities and are competent and empowered, and assurance that assets fulfil their purpose (ISO 55000-2, 2014).

A method for assessing and developing CE solutions from the perspective of AM is presented in Table 11. In the method, AM opportunities and threats are examined from the perspective of AM fundamentals using existing CE solutions as examples. The method focuses on the transition to a CE solution from an existing comparable linear solution from the perspective of the assets required.

Table 11. Method for assessing and developing circular economy solutions from the perspective of asset management.

Circular economy model and example	Threats from the perspective of asset management fundamentals	Opportunities from the perspective of asset management fundamentals
Circular supply-chain **Example:** Production of biomaterials from the side streams of pulp or paper production	**Value:** - Reduced utility value or obsolescence of old assets **Alignment, leadership & assurance:** - More actors and stakeholders in the value chain increase the complexity of the production system and the organization and pose new challenges for decision-making, leadership and the assurance of performance - Demand for interoperability of technical and information systems of different actors in the ecosystem	**Value** : - New purposes for old assets **Alignment, leadership & assurance:** - New operating networks enable mutual resource sharing
Product life extension **Example:** Caterpillar's remanufacturing concept	**Value:** - Recognizing when it is not feasible to extend the lifetime of machinery **Alignment, leadership & assurance:** - In order to use the concept, there is a need for extensive information on the utilization, condition and location of machinery. There might be a need for new information systems - Remanufactured machinery needs to be compliant with the requirements - New kinds of life cycle phases require the implementation of new assurance processes	**Value:** - cost reduction (reduction of new materials and energy consumption in production) - optimizing modes of use supports the extension of machinery lifetime **Alignment, leadership & assurance:** - Predictive maintenance enables early detection of wear and defects before failure occurs - Remanufacturing demands advanced performance monitoring and support processes to be successful. This enables indirect benefits such as decreased failures and disturbances, and new service opportunities
Sharing platform **Example:** Concept for renting machinery and power tools (e.g. Cramo)	**Value:** - Large amount of different users is a challenge for durability and asset management **Alignment, leadership & assurance:** - In order to use the concept, there is a need for extensive information about the location, condition and operational environment of the machinery. There might be a need for new information systems. - New life cycle phases require new assurance processes - There is a demand for assurance processes for the fulfilment of different customer needs	**Value:** - More efficient use of machinery (utilization rate) **Alignment, leadership & assurance:** - Functioning sharing platform enables better availability of machinery-related information - Advanced performance monitoring system enables new services that create added value for the customer (such as reducing failures by optimizing usage)

From the AM perspective, circular solutions offer many opportunities. They may extend the lifetime and increase the efficiency of assets, enable the recycling or reuse of components and equipment, offer new purposes for old equipment, and bring cost savings and indirect quality improvements through better availability and quality of information. However, CE solutions also introduce threats to AM such as complexity of the supply chain and information systems, management of new value elements, and the assurance of quality in the new production ecosystem.

4.4 Publication 4: Methods for value assessment of water and sewer pipelines

Motivation

Value assessment of water and sewerage networks is becoming increasingly important for owners, service providers and operators of water supply and sewerage systems. In many European countries, services such as network maintenance and renovation are provided mainly by public water utilities.

As outsourcing of maintenance duties has increased, asset valuation has become a factor of special interest. Owners and service providers are interested in monitoring the development of network condition over the long-term during maintenance partnership contracts and determining the optimal renovation timing and methods. Municipalities need fact-based reasons for investing in water and sewerage systems and service providers need to show the benefits of their services to the municipalities.

Many factors affect the condition of a network, making service life and value difficult to determine. The value of networks should be addressed holistically to include important perspectives such as safety and sustainability. Currently, water and sewage utilities use decision support methods such as documentation of service providers, manual inspections, cooperation with quality control and health care authorities, video recording and KPIs such as water loss-% per pipe kilometer or availability of clean water. However, these methods and variables might not be sufficient for measuring development of the value and condition of pipelines and supporting SAM.

Results

Publication 4 discusses existing SAM decision support approaches with a focus on the water and sewerage sector. Factors affecting the condition and durability of water supply and sewerage systems and key indicators used for measuring pipeline condition are presented. Table 12 illustrates the requirements for developing decision support for the water sector.

Table 12. Requirements for developing a strategic asset management support method for water systems.

Needs of the stakeholders	Variables indicating the value of the system	Sources of information
Condition of the network	Installation or renovation year, pipe material and type, structure of the system • number of valves (high number might indicate poor design quality) • installation technique • pipe corners and other parts that are challenging to renovate Video material (rarely used in clean water networks) Test results	History and maintenance data, maps, maintenance reports, video recordings, sensors and tests (loggers, radars, thermography, tracer gas, flow measurement etc.), unearthing the pipe, cutting the pipe open, experience, expert assessment
Reliability of the network	Water loss per inner area of the pipe times total length of the pipe, number of breakages, blockages, interruptions, leaks and blockages and resulting costs per year, unavailability-% per year	History and maintenance data, maps, tests (loggers, radars etc.)
Water quality	Sense perception, changes in quantities of certain substances (pH, sulfate, chloride, etc.)	Automatic and manual measurement
Increase in the value of production	Water loss per inner area of the pipe times total length of the pipe, invoiced water	History and maintenance data, cost and profit information from information systems
Decrease in maintenance and repair costs	Changes in cost of maintenance and repair activities, number of maintenance and repair activities performed compared to the long-term average	Maintenance reports, history and maintenance data
Reducing the risk and costs of environmental and safety hazards	Changes in perceived and actualized environmental and safety risks	Environmental and safety reports, maintenance reports, authorities
Increasing security of the network	Changes in perceived and actualized security risks	Security reports, expert assessment

Defining the needs of the stakeholders, such as water works, municipalities, citizens and service providers is a central part of the process. Based on the identified needs, variables indicating the value of the system are created. The third important step is to define the sources of information and the methods used in the gathering of information. In order to support water works and service providers in SAM, a simple checklist or a multi-criteria decision table could be sufficient. An illustration of a multi-criteria decision table for supporting SAM in a clean water system is presented in Table 13.

Table 13. An illustration of a multi-criteria decision table for a clean water system.

Figure	Level before renovation or maintenance	Level after renovation or maintenance	Level X years after renovation or maintenance
Water loss %	2	4	4
Unavailability %	3	3	4
Water quality	2	4	4
Maintenance and repair costs	2	3	3
Invoiced water	1	2	2
Flow measurement for condition assessment	2	3	2
Environmental and safety and security risks and costs	3	3	3

Seven figures were chosen to represent the value of the clean water network. The figures are presented on a scale from 0 to 5. The decision table emphasizes the holistic nature of value assessment regarding water and sewer systems. It aims at a more reliable measurement of the effectiveness of maintenance and renovation activities. As the main benefit, a more holistic value assessment method may improve trust between the various stakeholders, such as service providers and municipalities, and enable wider application of public-private cooperation.

4.5 Publication 5: A method for visualization of uncertainty and robustness in complex long-term decisions

Motivation

SAM related to infrastructure assets deals with long-term investments and long asset lifetimes. This long-term perspective calls for the use of scenarios and usually requires the opinions of different stakeholders and experts. It is often difficult for purely monetary indicators to capture all relevant issues. Additionally, because of the complexity and deep uncertainties involved in the decision context, determining the performance levels and related value of alternative strategies is challenging. Therefore, organizations' strategies should be robust, i.e. perform adequately irrespective of which scenario will materialize.

Results

Publication 5 presents a Strategy Robustness Visualization Method (SRVM) for assessing the robustness of alternative AM strategies (Figure 6). The method combines elements from two methods: Multi-Criteria Decision Analysis (MCDA) and Robust Decision-Making (RDM). The focus of the method is supporting climate change (CC) adaptation decisions.

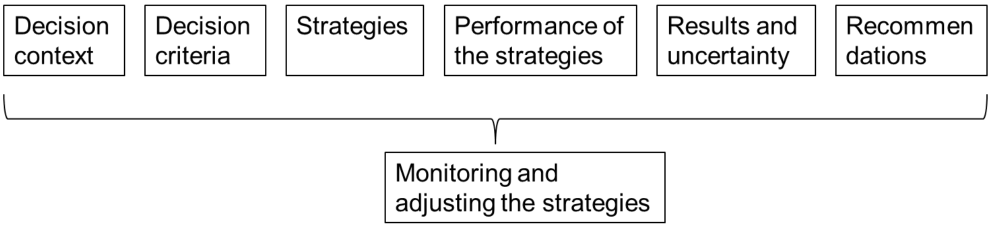


Figure 6. SRVM process.

During the first phase of SRVM, the decision context is defined. The phase includes identifying, selecting and involving stakeholders in the process and identifying all important factors affecting decisions. Additionally, scenarios for testing the performance of the strategies are selected or created. Next, the most important decision criteria are selected in cooperation with the stakeholders. In addition, the scale of each criterion is assigned in cooperation with the stakeholders. After selecting the decision criteria, the most important SAM strategies are selected. It is important that the number of decision criteria and strategies is kept reasonable by, for instance, voting for the most important criteria and strategies.

During performance of the strategies phase, each SAM strategy is assessed against each decision criterion, under all specified scenarios in turn. The measurement of strategy performance can be conducted by two means. First, stakeholders may assign performance scores based on their understanding of how a strategy performs under the specified scenarios. If there are several expert opinions, a distribution of scores should occur. Second, system modelling can be used to provide performance values. As a result, distributions for each of the scenarios are attained based on which the performance is measured.

In the results and uncertainty phase, the performance of the strategies is visualized with uncertainty ranges specified by the {min,max}-pairs of pessimistic and optimistic performance, in radar plot format. The performance of a strategy can be shown under all scenario combinations in one plot. The uncertainty is shown by the distance between the minimum and maximum lines, whereas robustness is shown by line-pairs which are close to each other for all scenarios (see Figure 7). The recommendations phase involves communicating the robustness, or non-robustness (vulnerability) of the strategies to the decision-makers. Pointing out key uncertainties is of central importance to the decision-makers irrespective of whether a robust strategy is identified. In monitoring and adjusting the strategies phase, the implemented SAM strategies are reviewed as the decision context changes.

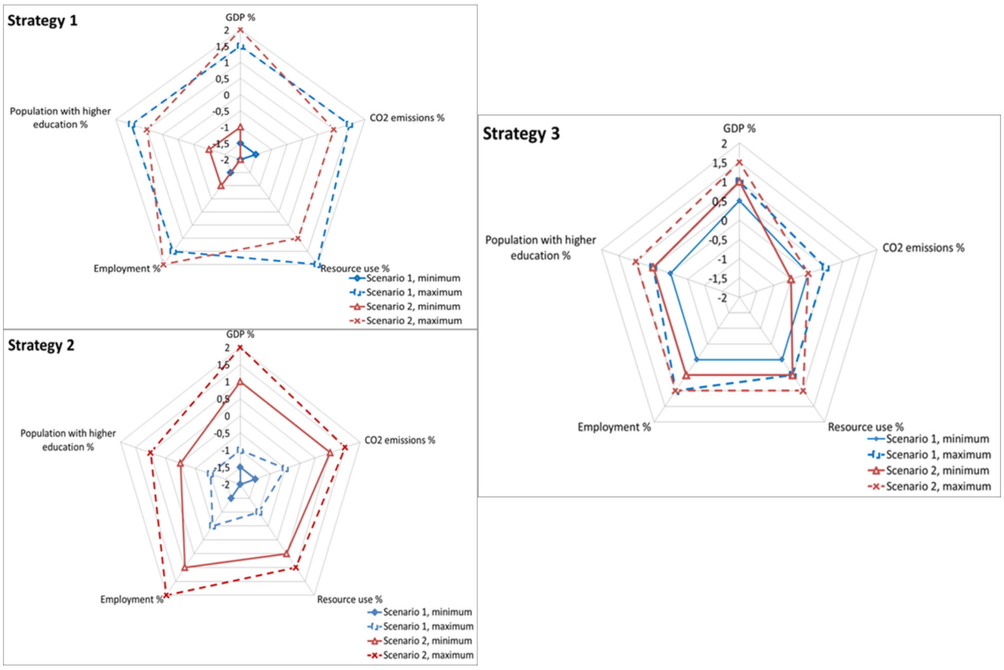


Figure 7. Performance of Strategies 1, 2 and 3.

In Strategy 1, there is high variance in both optimistic and pessimistic performance, but the performance is fairly similar in both scenarios. In Strategy 2, there is high variance in performance of the strategy in scenarios 1 and 2, but the variance between optimistic and pessimistic performance within the scenarios is fairly low. The variance between the scenarios and the optimistic and pessimistic performance values in Strategy 3 is low. Therefore, in comparison to Strategies 1 and 2, this is a robust strategy.

Figure 8 presents a case study regarding power sector adaptability in Northern Europe (for further details see Hanski, Rosqvist and Crawford-Brown, 2015). Using SRVM, four AM strategies are assessed: **no planned** CC **adaptation**, utilization of **capacity markets** that reward new or existing power generation capacity or demand response capacity in order to maintain additional capacity, use of different sources for **storing electric energy** and **additional connections** to other electricity markets to buy and sell electricity. The strategies are evaluated using eight decision criteria.

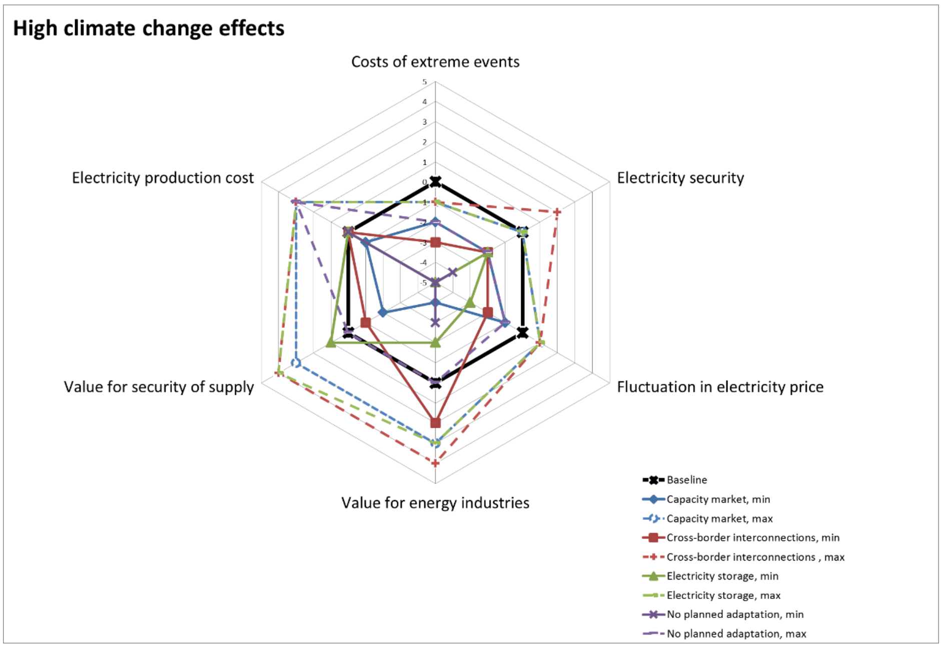


Figure 8. Case: Power Sector Adaptability in Northern Europe. High climate change scenario.

Figures 7 and 8 highlight different visualizations of the performance of strategies. Figure 7 shows the strategies in three figures, whereas Figure 8 shows all the strategies in the same figure.

4.6 Publication 6: Assessing climate change adaptation strategies – case of drought and heatwave in the French nuclear sector

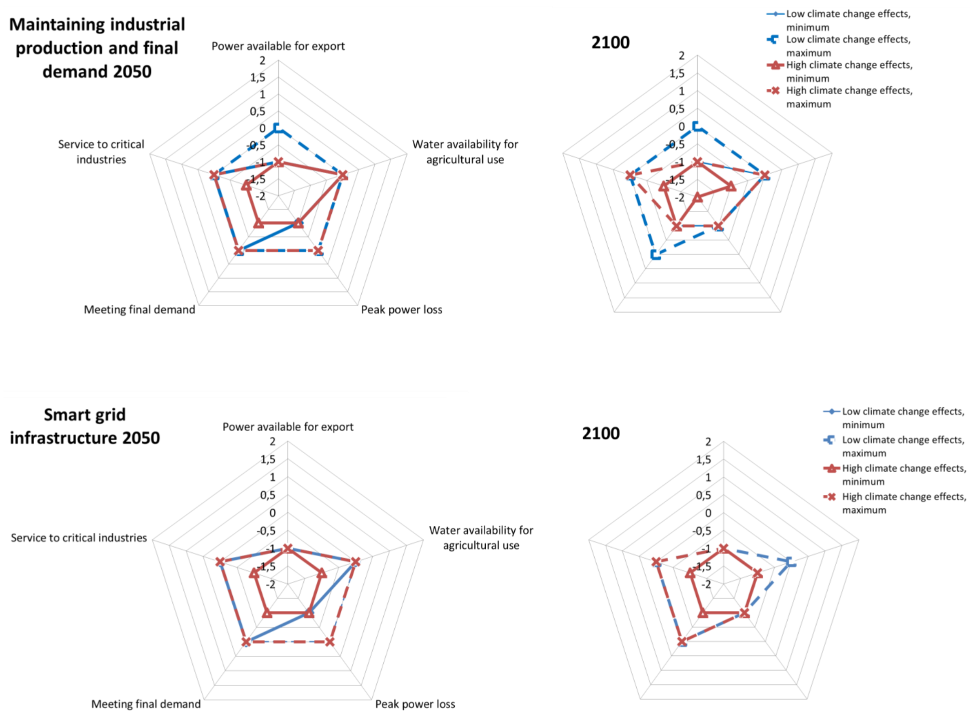
Motivation

Publication 6 delves deeper into supporting SAM decisions by analyzing their robustness and vulnerabilities. A case study analyzing the effects of drought and heatwaves on the French nuclear energy sector using Strategy Robustness Visualization Method (SRVM) is presented. If CC is not addressed, energy systems will be highly vulnerable to extreme weather events or shifts in weather patterns, such as changes in precipitation. Electricity generation may be significantly reduced due to decreased availability of water for cooling power stations during periods of drought, and restrictions on the return of water to rivers that are already at a high temperature due to heatwaves (Aaheim et al., 2013; EC, 2013). In addition, heatwaves and droughts lead to increasingly significant demand peaks, potentially causing overstress of energy infrastructure (EC, 2013).

Nuclear energy is a very important component of France's power supply. Any reduction in the ability of nuclear facilities to withdraw coolant water from rivers – and then return it – will reduce the power available to economic sectors. The French economic system depends on reliable and affordable energy. Due to the long life cycles of energy infrastructure, investments in energy systems should be made that are robust against climate scenarios such as lack of water due to CC.

Results

The SRVM follows the same process steps as presented in P5 (Figure 6). In the case study, three AM strategies are assessed: **No planned or automatic adaptation** strategy, where effects of climate and socio-economic change are considered without planned or automatic adaptation; **maintaining industrial production and final demand**, where residual power during a period of power curtailment is allocated in order to preferentially maintain industrial production and meet final consumer demand in France, while reducing power available for exports; and **smart grid infrastructure**, where residual power is allocated to maintain industrial production, final demand and exports, with a smart grid and buildings to allow for reduction of non-essential energy use during 'brown outs' (see Figure 9).



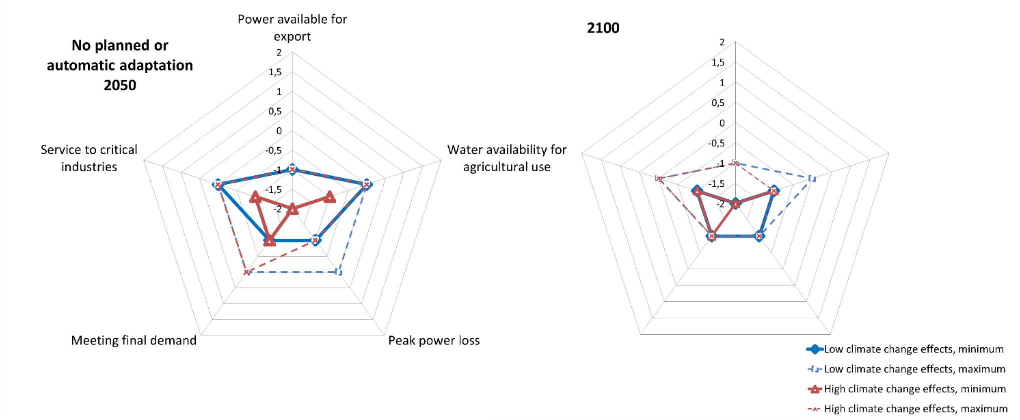


Figure 9. Case: Drought and heatwave in the French nuclear sector.

According to the results of the case study, the AM strategies "Maintaining industrial production and final demand" and "Smart grid infrastructure" appeared to be more robust than "No planned or automatic adaptation." To support the implementation phase, the identification of implementation actions that are common to both basic strategies is recommended. Additionally, identification of options for combining or changing strategies is recommended as new knowledge of future conditions emerges.

4.7 Overview of results

The main findings of the publications are presented in Table 14.

Table 14. Main findings of the publications from the perspective of the design science research.

	Problem awareness and proposal	Finding solutions and tentative design	Building and testing artifact	Evaluating and iterating	Communicating results
Research question	SQ1: What are the emerging trends and perspectives affecting strategic asset management in modern organizations?	SQ2: What methods exist for supporting the strategic asset management of organizations?	SQ3: What strategic asset management decision support methods can be developed for managing assets in complex and uncertain decision contexts?	SQ4: How can the developed strategic asset management support methods be tested in practice?	Main research question: How to manage assets in complex and uncertain decision contexts with strategic decision support methods?
Publications (P) related to the research question	P 1-6	P 1-6	P 3-6	P 3, 5-6	P 1-6 and the introductory part of the dissertation
Main findings	P1: Sustainability and information asset management perspectives, insights on how asset-based	P1: Decision support methods used in case companies	P3: Method 1: Method for assessing and developing circular economy	P3: Opportunities and threats identified in	Framework of emerging trends and perspectives affecting

	information is analyzed and utilized to support decision-making P2: Comprehensive list of indicators, perspectives and trends that should be considered in strategic asset management methods P3: Role of circular economy in asset management P4: Perspectives and trends affecting strategic asset management, such as network condition, sustainability and stakeholder perspective P5 and P6: Perspectives and trends affecting strategic asset management, such as stakeholder perspective, uncertainty, robustness and flexibility	P2: Classification of methods supporting strategic asset management P3: Asset management fundamentals, introduction of circular economy models P4: Classification of methods for strategic asset management used in water and sewage sector P5 and P6: Introduction of methods such as real options, scenario methods, participatory techniques, RDM and MCDA	solutions from the perspective of asset management P4: Method 2: Strategic asset management methods for water and sewage sector decision-making P5 and P6: Method 3: SRVM (Strategy Robustness Visualization Method)	real-world case studies P5: Preliminary testing of method through examples and a case study "Power Sector Adaptability in Northern Europe" P6: Case study "Drought and heatwaves in the French nuclear sector"	strategic asset management Framework for supporting the selection of strategic asset management methods

The findings of P1 are twofold. First, it discusses the importance of information management and sustainability in SAM (SQ 1). It provides a review of the state of SAM in selected frontrunner organizations. Second, it provides input on the state of the art of AM decision-making and which methods are used in frontrunner organizations.

P2 creates a foundation for the development and evaluation of methods supporting SAM. It contributes to framework modelling (SQ 2) by providing a systematic literature review of the available methods supporting SAM. Additionally, it deepens the understanding of their classification and characteristics, focusing on the indicator groups used in the methods. P2 provides a list of indicators for SAM and a preliminary version of the framework of emerging trends and perspectives affecting SAM.

The main finding of P3 is the introduction of CE into the SAM context (SQ 1). Similarities and differences of CE and AM are highlighted. Additionally, a method for classifying, assessing and developing CE solutions from the perspective of AM is presented (SQ 2). The method can be used for assessing both novel CE-based solutions and production systems and existing solutions. The method was tested through real-world case studies with different CE solutions (SQ 4).

P4 deepens our understanding of the factors affecting SAM. Perspectives and trends affecting SAM such as sustainability and stakeholder perspective are presented, which contribute to the problem definition stage (SQ 1). Examples of decision support methods used in the water and sewage sector are presented. The publication also provides guidance for the classification of methods for supporting SAM (SQ 2). Methods for SAM in the water and sewage sector are also presented (SQ 3).

The main finding of P5 is the introduction of a novel method for supporting SAM (SQ 3). It provides guidance for the classification of decision support methods. Moreover, the publication deepens our understanding of the aspects of strategic management that also affect SAM, such as uncertainty, robustness and flexibility (SQ 1), and utilization of approaches such as real options, scenario methods, participatory techniques, RDM and MCDA (SQ 2). Preliminary testing of the method through examples and a case study is also presented. P6 builds on the outcome of P5 and presents a case study that utilizes the developed decision support method (SQ 1-4).

5. Discussion and conclusions

5.1 Managing assets in complex and uncertain decision contexts

This thesis focused on identifying, developing and testing methods for supporting SAM decisions in complex and uncertain decision contexts. The main research question was as follows:

> "How to manage assets in complex and uncertain decision contexts with strategic decision support methods?"

The main research question was answered by dividing it into four subquestions (SQ). The subquestions dealt with key trends and perspectives related to SAM, existing methods for supporting SAM and developing and testing novel methods using Design science approach (DSR). Therefore, the main research question was answered by clarifying the concepts, emerging trends and perspectives affecting SAM, classifying the methods for supporting SAM, and developing and testing novel methods for the identified research gaps.

> SQ 1: What are the emerging perspectives and trends affecting strategic asset management in modern organizations?

This dissertation explored the concepts of asset, asset management, strategic management, and uncertain decision contexts for strategic asset management. Key concepts such as complex and uncertain decision context, strategic position and the related external and internal view of an organization were introduced. The strategic perspective of AM is covered in some publications (Komonen, Kortelainen and Räikkonen, 2006; 2012; Too, 2012; El-Akruti, Dwight and Zhang, 2013). However, a more in-depth and explorative analysis of trends and perspectives affecting SAM was needed.

A number of examples of emerging factors affecting the AM decision-making of organizations are presented in the AM literature. These include stakeholder needs and requirements (Liyanage, 2012), sustainability, resilience, life cycle management, community demands, information management, and new types of governance arrangements (Brown et al., 2014), changes in demand and the competitive environment, economic obsolescence, security of economy, climate change, compliance with requirements, technological development, acquisitions, changed operating practices and requirements, wear and aging, and technical and environmental obsolescence (Hastings, 2010; Komonen, Kortelainen and Räikkönen, 2012; Liyanage, 2012). The publications and review of the SAM, strategic management and decision support literature revealed a number of perspectives and emergent trends that should be considered when supporting SAM decisions. Figure 10 highlights the emerging trends and perspectives that were considered crucial for supporting SAM decisions.

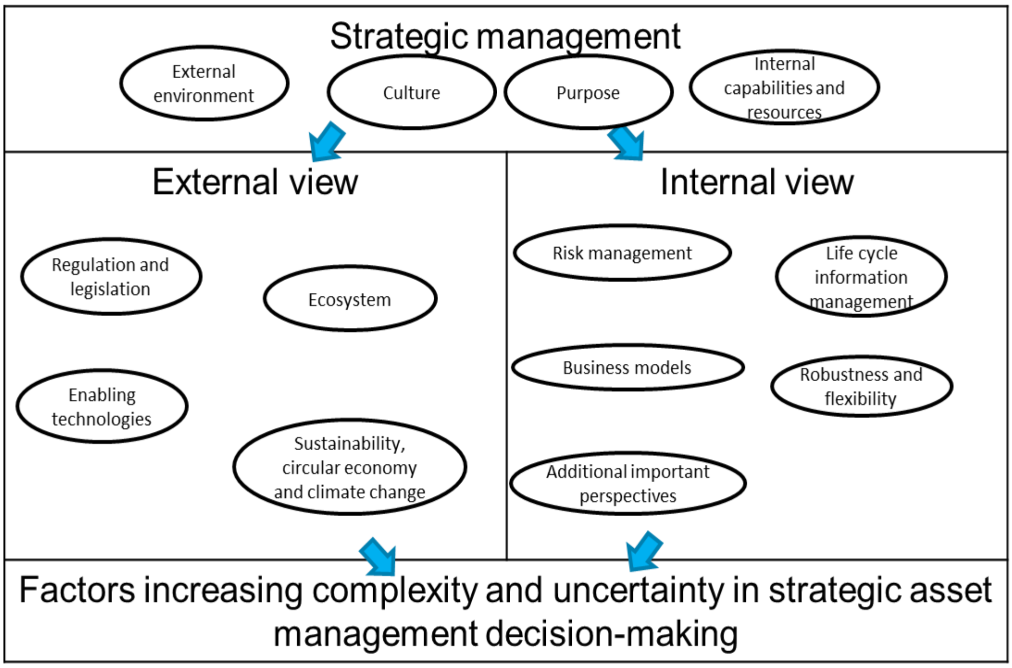


Figure 10. Framework of emerging trends and perspectives affecting strategic asset management.

The rationale behind the framework is that strategic management at the organizational level guides and affects SAM decisions. Strategic management consists of an internal and external view, purpose and culture (e.g. Johnson, Scholes and Whittington, 2008). In this dissertation, the focus is on the external and internal view that consist of the emergent trends and crucial perspectives that should be considered in SAM decisions. These identified emerging trends and perspectives (factors) increase the complexity and uncertainty in SAM decision-making. The rationale for selecting these trends and perspectives is that they were identified as emerging factors when developing methods supporting SAM. They were considered important and actual, and could change the way assets are managed at the strategic level. However, they have been limitedly considered in the SAM literature and even less in practice (e.g. Mahmood et al., 2015).

There is a strong interconnection between many of these emerging trends and perspectives, such as servitization, enabling (digital) technologies and circular economy. The external view consists of regulation and legislation, sustainability and climate change, enabling technologies, and the ecosystem. Regulation and legislation cover the key requirements and enablers regarding regulation, legislation and the most important stakeholders. Sustainability, CE and climate change cover important perspectives that aim to address challenges such as scarcity of resources and the long-term efficiency and effectiveness of a company with regard to environmental, social and financial perspectives. Enabling technologies cover the technology perspective and the impact of digitalization. Ecosystem includes the ecosystem, market characteristics, and customer's decision context perspectives.

The internal view consists of business models, risk management approach, life cycle information management, robustness and flexibility and other important perspectives. Business models include the business model perspective and servitization trend, which has a major impact on current and future business models. Life cycle information management is a combination of the information, life cycle and fleet management perspectives. Robustness and flexibility cover the robustness and adaptive management and flexibility perspectives.

When considering SAM decisions, the framework above supports the evaluation of which emergent trends and perspectives should be in focus in a given decision context. From the perspective of publications, P1 focuses on life cycle information management and sustainability, and CE and climate change; in P3 the focus is on sustainability, CE and climate change, risk management, and life cycle information management, whereas P5 and P6 address sustainability, CE and climate change, regulation and legislation, risk management, and robustness and flexibility.

On one hand, SAM should currently – and increasingly in the future – emphasize sustainability, circular economy and climate change. It should be noted that each of these broad trends covers a large number of concepts and areas, more than enough to be covered by a single method. As an example, a large number of aspects, such as protection of environment, governance and transparency, are introduced in this dissertation in relation to sustainability, while climate change includes, for example, numerous slow incremental changes and various categories of extreme events and the methods for adapting to and mitigating them (see e.g., Epstein and Roy, 2003; Epstein, 2008; Hanski, Keränen and Molarius, 2018).

On the other hand, life cycle information management and enabling technologies are crucial enabling factors in addressing these trends. Emerging technology and concepts such as big data, artificial intelligence, advanced analytics and industry 4.0 have the potential to seriously disrupt SAM. However, in order to transform the novel solutions into successful business, the business model perspective is crucial. Additionally, in the case of very long-term decisions regarding complex systems – such as those related to climate change – risk management and robustness and flexibility are crucial perspectives.

Although the framework was primarily developed inductively during the development and testing of the methods and while preparing the publications for this dissertation, it is also influenced by other frameworks (e.g., Komonen, Kortelainen and Räikkonen, 2006; Van der Lei, Wijnia and Herder, 2012; ISO 55000-2, 2014). The framework supports the development of methods for supporting SAM. It forms a baseline for which trends and perspectives SAM should consider.

SQ 2: What methods exist for supporting the strategic asset management of organizations?

P1 states, in line with Komonen, Kortelainen and Räikkönen (2012), that decision-making in companies is still based on intuition, expert opinion and experience and asset-based information is usually not used at the strategic level. Therefore, there is a need for introducing methods to support SAM decisions and guidelines on which methods could be used in which decision contexts.

There are several complementary methods for supporting strategic decision-making (see e.g., Hinkel and Bisaro, 2016; Hanski, Keränen and Molarius, 2018). In this dissertation, a variety of methods for supporting SAM decisions were introduced. The methods originated from various disciplines, such as decision support, risk management and AM. Their applicability for supporting SAM in organizations was analyzed. There are several factors affecting the selection of a decision support method for SAM. There are some classification frameworks for methods supporting SAM (e.g. AWWARF, 2001; Herder and Wijnia, 2012), which aim at supporting the selection of decision support methods for certain decision contexts. However, there is a need for classification frameworks that consider uncertain and complex decision contexts and other crucial factors. Based on the existing classifications and experiences during the research process, the main dimensions to be considered when developing or selecting methods for supporting SAM are:

1. Resource availability
    a. data availability and quality
    b. analytics and methodology competence availability
    c. domain expertise availability
    d. monetary resource availability
2. Complexity and uncertainty of decision context
    a. characteristics of asset or system
    b. application area
    c. time horizon of analysis
    d. key trends and perspectives

Resource availability refers to the availability and quality of data, analytics and methodology competence, domain expertise, and monetary resources. It is crucial that domain, analytics and methodology experts are available for the method to be developed, used and maintained. Data availability and quality considerations include factors such as availability of qualitative and/or quantitative data that is reliable and in usable format (e.g. ISO 55000-2, 2014). Analytics and methodology competence limits the selection of SAM decision support. Certain methods such as MCDA and RDM require considerable expertise, whereas checklists and guidelines are lighter from a methodological perspective. Domain expertise enables the use of expert opinion based methods, such as some applications of MCDA and participatory methods. Monetary resources are an enabler for the use of decision support methods. Generally, the more complex the method and more extensive its data requirements, the more monetary resources the decision support method requires.

The decision context determines what the decision is about (Salo and Hämäläinen, 2010). The complexity and uncertainty of the decision context increase based on the characteristics of the analyzed asset or system, the application area, the time horizon of analysis, and the key trends and perspectives included in the analysis. These factors introduce complexity and uncertainty into the decision-making process and determine the development or selection of decision support methods: the characteristics of the asset or system, such as complexity (van der Lei, Wijnia and Herder, 2012), and the application area, such as electricity infrastructure, process industry, manufacturing, tourism or public sector (Hanski, Keränen and Molarius, 2018), have a major impact on the method selection. The time horizon of analysis is also crucial to the selection of decision support method. Furthermore, there is a difference in the requirements for uncertainty management if the SAM decision considers short-term implications (1-3 years), very long-term implications (75+ years) or something in between (see e.g., Hanski, Keränen and Molarius, 2018). Key trends and perspectives introduce complexity and uncertainty to the decision context. As an example, sustainability, CE and climate change introduce considerable complexity and uncertainty to the decision context compared with only financial requirements. The framework of emerging trends and perspectives such as legislation and regulation, ecosystem and enabling technologies give guidelines for developing methods for supporting SAM decisions. Figure 11 positions the identified methods for supporting SAM decisions into a classification framework according to the complexity and uncertainty of the decision context and resource availability.

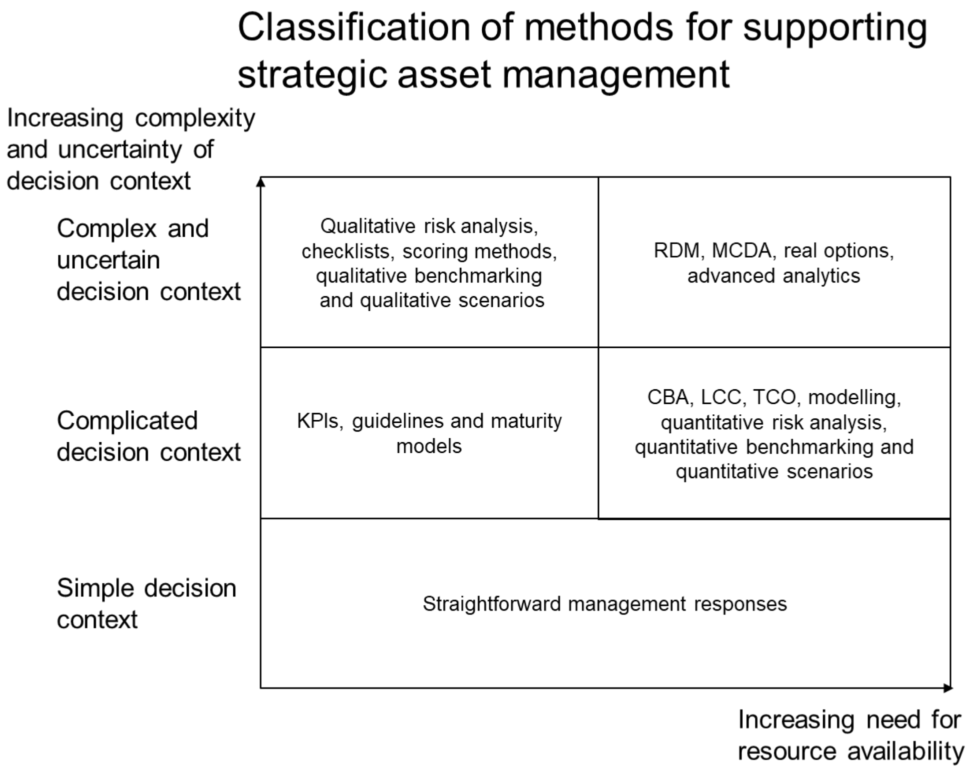


Figure 11. Classification framework for supporting the selection of SAM methods.

The classification framework for supporting the selection of SAM methods has two dimensions: complexity and uncertainty of decision context and resource availability. In line with Snowden and Boone (2007), the decision context is categorized as simple, complicated, and complex and uncertain. In the simple decision context, strategic responses are based on establish practices. In this context, decisions may be purely intuitive or include the use of existing decision support methods. In the complicated decision context, several competitive decision options are analyzed. Expertise is required to understand the options and the consequences of the strategic responses. In the complex and uncertain decision context, the consequences of decisions can be understood only in retrospect.

Experiments, sensing the impacts of the experiments, and responding to the differences between expectations and reality are required.

The main message of the classification framework is that it is crucial to select a method that is a good fit for the given decision context. The classification framework supports the identification of the SAM decision context and gives guidance on what kinds of methods could be used in which decision situations. It is important to consider in depth both the different criteria included in the decision context and the resource availability for development and use of the method. Simple methods, such as checklists and scoring models, are potentially highly suitable for complex and uncertain decision contexts as they facilitate experimentation, which is needed to address the inherent challenges of these kinds of decision contexts. Use of RDM, MCDA and real options are suitable for complex and uncertain decision contexts if enough resources are available, although qualitative risk analysis and scenarios are less resource demanding. However, in order to obtain reliable qualitative scenarios the availability of domain expertise is crucial.

The presented classification framework is mainly illustrative and serves as an example of how decision support methods could be classified. Applications for certain methods could be positioned in either complicated, or complex and uncertain, categories. Qualitative methods are in some cases more suitable than quantitative for complex and uncertain decision contexts due to limited availability of reliable data. Some qualitative methods may be highly demanding from the resource availability perspective, while certain quantitative methods may be less demanding. Checklists and guidelines may be highly appropriate for a certain decision context, for instance if more sophisticated methods are too resource demanding or if information gathering or analysis are challenging. In addition, simple methods can be useful for supporting the ideation and concept development phases where the decision context can be extremely complex and uncertain.

> SQ 3: What strategic asset management decision support methods can be developed for managing assets in complex and uncertain decision contexts?

Complex and uncertain decision contexts relate generally to sectors and industries that have expensive investments in assets that have long life cycles. This subquestion was addressed by developing novel decision support methods for many of the key emerging trends and perspectives. These included, for instance, sustainability, CE, and climate change. Existing methods do not sufficiently consider all of the necessary trends and perspectives. Some research that considers supporting holistic SAM decision-making has been done on risk-based AM and infrastructure AM (van der Lei, Wijnia and Herder, 2012; Mahmood et al., 2015; Wijnia, 2016). Additionally, comprehensive SAM frameworks (El-Akruti, Dwight and Zhang, 2013; Attwater et al., 2014; ISO 55000-2, 2014) supported the creation of the novel methods in this dissertation.

The focus of this subquestion was on developing methods that address the most relevant trends and perspectives that are not often considered in SAM. The developed methods complement the current existing decision support methods. Based on the identified emerging trends, perspectives and existing methods, the following novel SAM decision support methods are introduced:

1. Method for assessing and developing CE solutions from the perspective of asset management (P3)
2. Strategic asset management frameworks for water and sewage sector decision-making (P4)
3. Strategy Robustness Visualization Method (P5 and P6)

From the SAM perspective, CE solutions may not always be viable. The first method (P3) focused on what kind of impact CE has on SAM. Depending on the usage of the method, it can be considered either a qualitative benchmarking method or a checklist. The method shares similarities with SWOT analysis (Strengths, Weaknesses, Opportunities and Threats), which is a commonly used method in strategic management. It addresses the perspectives and trends of CE and information management. The CE perspective has been considered only limitedly in SAM (Korse et al., 2016). The role of information is crucial in SAM (Ellen MacArthur Foundation, 2016) and assessing the role of information management in enabling CE in SAM is a novel approach. In this method, SAM is considered through the AM fundamentals (ISO 55000-2, 2014) and CE through a classification based on Bocken et al. (2016) and Lacy and Rutqvist (2016) and company examples. The method is suitable for assessing or benchmarking both existing circular solutions and potential concepts at the ideation phase. The goal of the method is to visualize the challenges and opportunities for SAM related to the transition from linear to circular business.

The second method (P4) focused on developing a holistic decision support system for SAM in the water and sewage sector. It can be used as a checklist, scoring method or data provider for an MCDA application. Existing criteria for supporting SAM decisions focus on the technical and economic condition of the network including pipe material, internal and external load, conditions preceding use, pressure and failure mechanisms (Kekki et al., 2008) or monetary assessment methods such as current replacement costs and/or net present value. However, inclusion of technological and managerial, legal and institutional, political and social, financial and economic and environmental criteria is also proposed (Grigg, 2005). Suggested methodologies for supporting SAM decision-making include a spreadsheet with weighted evaluation criteria, performance measures and project ranking, and multi-criteria decision analysis (AWWARF, 2001). The method is suitable for, for instance, setting requirements for SAM in water utilities and assessing the development of value in water systems. It may improve trust between service providers and municipalities by taking a more transparent and holistic perspective in SAM, and thereby enable wider application of public-private cooperation.

The third method (P5 and P6), the Strategy Robustness Visualization Method (SRVM), supports SAM by visualizing and assessing the uncertainties and robustness of alternative long-term strategies. It is a combination of RDM and MCDA approaches. In long-term SAM investments it is difficult for purely monetary indicators to capture all relevant issues. Approaches such as CBA struggle in monetizing and aggregating all the costs and benefits, presenting plural values and taking uncertainty into account (Scrieciu *et al.*, 2014). This long-term perspective and its related uncertainties call for the use of scenarios and the opinions of different stakeholders and experts. Furthermore, in such cases, modelling of performance with formal methods such as simulation cannot always be done. Because of the deep uncertainties, organizations' strategies should be robust, which means that any strategy should perform adequately irrespective of which scenario will materialize (e.g. Lempert et al., 2006). SRVM takes the deep uncertainties related to long-term strategies, complex phenomena and various stakeholder perspectives into account and enables a rough assessment of robustness and vulnerabilities of alternative SAM options.

The developed methods can be positioned into the framework for supporting the selection of SAM methods (Figure 11). All of the developed methods are suitable for supporting SAM decisions in complex and uncertain decision contexts. However, the resource availability needs vary between the methods. The first method requires relatively modest resources, i.e. expertise on the selected circular solutions, similar linear solutions and asset management. The second method requires data on various criteria that determine the performance and value of the water system, which might be difficult to obtain. Additionally, expertise on the water system is required. The third method requires considerable resources such as hard-to-obtain quantitative data, expertise in various fields for building socio-economic scenarios and determining decision criteria and their performance, and methodological expertise.

> SQ 4: How can the developed strategic asset management support methods be tested in practice?

The fourth subquestion deals with testing the developed decision support methods and the methodology for testing the methods. The methods were tested following the guidelines of DSR (Hevner et al., 2004; Vaishnavi and Kuechler, 2004; Holmström, Ketokivi and Hameri, 2009). The developed tentative designs (methods) were refined and evaluated during the iterative development rounds (Vaishnavi and Kuechler, 2004; Holmström, Ketokivi and Hameri, 2009). Case study research (Yin, 2003; Koskinen, Alasuutari and Peltonen, 2005) was the main research method utilized in testing and evaluation. By means of case study research, the methods were implemented and refined in multiple contexts. The methods were also examined in relation to the existing theoretical discourse of SAM (Holmström, Ketokivi and Hameri, 2009) and were further evaluated through presenting them in scientific publications and conferences.

The first and third methods presented in publications 3 and 5-6, respectively, were tested in case studies. The first method focused on five case examples representing different types of CE solutions (see Table 11): production of biomaterials from the side streams of pulp and paper production; recycled paper production; a remanufacturing concept; a concept for renting machinery and power tools; and a cost per performance concept. The opportunities and threats of these concepts for SAM in comparison to similar linear models were assessed in a workshop setting. The experts that participated in the assessment process had extensive experience from the asset management field.

The third method included two in-depth case studies: 1) Power sector adaptability in Northern Europe and 2) Drought and heatwave in the French nuclear sector. The case studies involved real stakeholders at many stages of development and testing of the method. The stakeholders played an important role in selecting relevant scenarios, determining decision criteria and SAM strategies, and evaluating the performance of the strategies.

The first case study dealt with CC adaptation in the renewable energy sector, more specifically, how CC can affect variable renewable electricity production and electricity demand in Northern Europe up to 2050. The goal was to assess the performance of selected SAM strategies for adapting to climate change. The SAM strategies were assessed using several decision criteria. The first case study was demonstrated at the European Climate Change Adaptation (ECCA2015) conference with five participating stakeholders to an audience of 15 researchers and industry experts.

The second case dealt with CC adaptation in the French nuclear power sector. The French economic system depends on reliable and affordable energy and any reduction in the ability of nuclear facilities to withdraw coolant water from rivers, and then return it, will reduce the power available to economic sectors. Electricity generation from the nuclear power plants may be significantly reduced during periods of drought. In addition, heatwaves and droughts lead to increasingly significant demand peaks, potentially causing overstress of the energy infrastructure (EC, 2013). In this case study, SRVM was used to assess two SAM strategies and a baseline strategy for years 2050 and 2100. The second case study was demonstrated to experts at the European Commission in Brussels.

5.2 Theoretical contributions

There are three types of possible contributions in DSR: design artifact related contributions; foundations, such as theories, frameworks, constructs, models and methods; and methodology-related contributions (Hevner et al., 2004). Many of these types are addressed in this dissertation. Several theoretical contributions are made to the ongoing discussion regarding SAM and methods supporting SAM decisions in complex and uncertain decision contexts. This dissertation has made contributions to the theoretical discussion regarding the role of strategic management and decision support methods in the SAM literature. It has introduced a novel classification of key emerging trends and perspectives and methods supporting SAM, and described the linkages between assets, AM, strategic management, complex and uncertain decision contexts and SAM.

First, a holistic framework of emerging trends and perspectives affecting SAM was presented. These trends and perspectives will change the way assets are managed at the strategic level in the future. The framework complemented the limited literature available on the emerging trends and perspectives affecting SAM (e.g., Hastings, 2010; Komonen, Kortelainen and Räikkönen, 2012; Liyanage, 2012; Brown et al., 2014).

In addition, this dissertation deepens the understanding of some key trends and perspectives and their relationship to SAM. The thesis has built a solid argumentation for the inclusion of sustainability, CE perspectives and climate change in SAM. Decision-making related to sustainability and life cycle information management are implemented at varying levels in manufacturing and process industry organizations. In this dissertation, guidelines for assessing and developing these practices in organizations were presented. When moving from linear to circular solutions, asset managers have to consider a range of new factors. SAM and CE objectives are largely aligned, as both aim to increase resource efficiency and prolong the useful life of machinery (Hanski and Valkokari, 2018). This dissertation complemented the existing theory on CE and SAM by developing a theory on the relationship of SAM, sustainability and CE and on the impact of SAM on sustainability and CE implementation. Climate change is only limitedly considered in SAM (Mahmood et al., 2015), and the different aspects such as slow and fundamental changes in natural conditions, extreme weather related events, and less typical seasonal weather patterns (Kortschak and Perrels, 2013) are not considered.

Secondly, this thesis deepened the understanding of methods supporting SAM and provided a classification of these methods. A list of methods for supporting SAM decision-making was identified and introduced. A novel classification of methods supporting SAM based on resource availability and complexity and uncertainty of decision contexts was also presented, which complements some of the existing classifications (AWWARF, 2001; Herder and Wijnia, 2012; Watkiss et al., 2015; Shafiee et al., 2019). Watkiss et al. (2015) present a classification of traditional decision support (CBA, cost-effectiveness analysis and MCDA) and decision-making under uncertainty (real options analysis, RDM, portfolio analysis and iterative risk management) for a climate change adaptation context. Furthermore, they argue that the methods for decision-making under uncertainty are complex and resource-intensive. Compared with this classification, Figure 12 provides a more detailed classification, with more categories for uncertainty and complexity, that is tailored for SAM. Shafiee et al. (2019) focus on the oil and gas industry and identify a list of decision support methods including operational research, CBA, real options analysis, LCC, environmental life cycle assessment, Monte-Carlo simulation, decision tree analysis, MCDA, fuzzy logic analysis and artificial intelligence. This list is more comprehensive than the classification presented in this dissertation, and should be considered when further developing the classification.

Thirdly, novel decision support methods for SAM were developed. DSR was utilized in developing the methods. DSR has been used only to a limited extent in the management and AM fields (e.g. Van Aken and Romme, 2009). Therefore, this dissertation builds on the theory of utilizing DSR in SAM research. The methods contributed to the strategic decision support and SAM literature. The methods supporting SAM were applied to different application areas (water and sewage, electricity production, manufacturing and maintenance, general assets) but they all aim at addressing the challenges of the changing internal and external operating environments. This dissertation also addressed the challenge of how companies with an installed asset base should best deal with the changes brought by CE solutions. In this case, it contributed to the SAM and CE fields by providing a method for assessing and developing CE solutions from the perspective of SAM. In this dissertation, a novel method for supporting SAM in the water and sewage sector was presented. It included a list of key performance indicators and formed a basis for developing multi-criteria decision analysis methods for supporting SAM decision-making in the sector.

In addition, this dissertation dealt with the extreme uncertainties related to very long-term decision-making, assets with long life cycles, and climate change. A novel method for supporting SAM under deep uncertainty was presented. The method, SRVM, is suited to assessing complex long-term AM strategies especially related to climate change adaptation. Extreme events and climate change are only limitedly, if at all, considered in the current methods used for supporting SAM decisions (Mahmood et al., 2015; Komljenovic et al., 2016). SRVM is a novel combination of stakeholder perspective, scenario analysis, robust decision-making and multi-criteria decision analysis approaches. SRVM contributes to promoting the systematic use of future studies approaches, such as scenario analysis, as a part of SAM.

Fourthly, the case studies in this dissertation represent decision situations that have considerable theoretical importance. The analysis of CE solutions from the SAM perspective, the renewable energy case in Northern Europe and the impact of drought and heatwave on the French nuclear energy sector are all explorative studies with considerable novelty from the theoretical perspective. Previous studies considering CE opportunities and threats, asset management and production systems were not found, and the case examples have not previously been explored in the way presented in this dissertation. Both renewable energy and the French nuclear case combine novel modelling and expert opinion based data to provide completely novel information concerning the possible climate change impacts on the respective systems, the related uncertainties and vulnerabilities, and the robust strategies to counter them. Therefore, the research contributes to deepening the theoretical understanding of the selected case studies.

5.3 Managerial implications

The main managerial implications of this dissertation relates to deepening the understanding of the strategic perspective in AM. This dissertation gives an extensive overview of the emerging trends and perspectives that asset managers should consider in strategic decision-making. It presents a framework of emerging trends and perspectives to be used when developing or assessing SAM at, for instance, the ecosystem, company, plant, or department level. It serves as a checklist of crucial perspectives that SAM should consider. In addition, it highlights the importance of ensuring the link between strategic management and SAM.

The dissertation and the publications shed light on topics that are important for asset managers and other decision-makers. Out of the individual trends and perspectives, the implications of CE, sustainability and climate change for SAM are highlighted. These have profound implications on how assets should be managed and they have yet not been addressed in practice at a necessary extent. In order to meet the challenges of resource sufficiency and a changing climate, AM strategies need to focus more strongly on these aspects.

In addition, the role and implications of information, digitalization and related concepts are currently of a high priority for managers responsible for SAM. Novel technologies, data, and analytics capabilities enable a variety of new asset-based services and better means for the optimization of asset systems. Asset managers should be aware of how their asset base is affected by the opportunities and threats of digitalization and other technological developments. Servitization calls for considering the customer perspective in the development of asset-based services. In particular, understanding the contexts of customers' and stakeholders' decision-making is crucial. Furthermore, organizations should understand the characteristics of the market they are operating in and the ecosystems that they are part of in creating value for the end customer.

These external trends and perspectives require close consideration of the internal strategic aspects of organizations. A business model perspective is becoming increasingly important for translating SAM activities and services into value for customers, while risk management and managing uncertainty are integral parts of SAM. The role of information management has always been crucial in SAM, however, the digitalization trend has emphasized its importance even further and enhanced information management practices have enabled novel life cycle and fleet management applications and services. The life cycle management perspective is also gaining importance due to the increasing need for considering sustainability and CE in SAM. In addition, partly due to the various trends and perspectives presented in this dissertation, SAM decisions contain considerable uncertainty. To answer to this uncertainty asset managers should consider the robustness of decision alternatives. Other important perspectives for supporting decision-making in highly uncertain decision contexts include adaptive management and flexibility.

These trends and perspectives call for methods for supporting SAM decision-making. For this reason, this dissertation provides a framework of methods supporting SAM based on resource availability and the complexity and uncertainty of decision contexts. With this framework, asset managers can gain an overview of available methods and select the method that is most suitable for their decision situation. In addition to the available methods from the literature, several novel methods are developed in this dissertation.

The managerial implications of the individual publications are laid out in the following paragraphs. P1 provides a review of the state of the art of information asset management and sustainability in leading manufacturing and process industry companies. It presents some of the best practices in the field that could be transferable also to other industries. Using the results and the guidelines adopted from the standard, companies can assess the maturity of their organization by considering these aspects.

P2 deepens our understanding of the characteristics of decision support methods for SAM. It introduces the indicators and uncertainty management methods currently used in existing methods. Additionally, it discussed sustainability and how it should be taken into account in SAM. A method for connecting sustainability principles and SAM is presented to enhance the sustainability of SAM.

Managerial implications of P3 include new knowledge about the impact, opportunities and threats of CE models on AM. The method and case studies help companies and other organizations to better assess and develop their processes and business models towards CE.

P4 deepens the understanding of factors that should be considered when developing strategic-level decision support methods for the water and sewage sector. It presents a variety of indicators and SAM methods utilized in the sector. It presents a list of the most important indicators that could be used as a basis for developing a multi-criteria decision analysis method regarding clean water networks. A method for supporting SAM decisions in the water sector is also presented.

P5 and P6 discuss the implications of climate change on SAM decisions. They introduce the concepts of robustness and flexibility that should be central in decision situations that involve deep uncertainties. A novel Strategic Robustness Visualization Method (SRVM) is presented. The SRVM supports SAM by helping to determine scenarios for the future operating environment of the assets. It supports the assessment of AM strategies in the identified decision context. The goal of the method is to determine the strategies that perform within the allowed boundaries in all scenarios, i.e. strategies that are robust. The presented case studies also deepen understanding of the implementation of the SRVM method in practice.

5.4 Suggestions for further research

This dissertation focused on supporting SAM decisions in complex and uncertain decision contexts. This research has lit up several new avenues of research. Firstly, further development and testing of the developed methods and frameworks is needed. Further research will be needed for developing sector or application area specific decision criteria, methods and frameworks. Additional case studies are also needed to validate the decision support methods. This work would also support the further development of the classification framework for methods supporting SAM.

Secondly, key trends and perspectives should be better emphasized in the future research and standardization works related to SAM. In addition, they should be covered in developing new KPIs and decision support methods for SAM. Providing the emerging trends and perspectives affecting SAM is just the starting point for implementing a more holistic view of SAM.

Thirdly, SAM plays a major role in striving for a more sustainable world. More research is needed on the role of sustainability and CE in SAM. Measuring the impact that SAM has or might have on sustainability and climate change mitigation and adaptation is of utmost importance. Novel decision support methods are needed to cover all of the important perspectives related to sustainability and CE. In addition, they need to be implemented and tested in practice. SAM has potential to contribute greatly to climate change mitigation and adaptation strategies. More research is needed towards integrating climate change considerations into SAM frameworks and methods supporting SAM.

Fourthly, information management systems should be developed to support SAM decision-making and the consideration of emerging trends and perspectives. There is a need for research on managing asset based information, analyzing it and utilizing it for supporting SAM decisions. Asset based information should be better utilized in management systems. Digitalization including innovations related to novel technologies, advanced analytics such as machine learning and other areas of artificial intelligence offer much potential for supporting SAM-related decisions. Information management is also an important enabler for sustainability and CE and further research is needed in predicting and visualizing the development of sustainability and SAM indicators and increasing transparency and the use of real-time information in decision-making.

Finally, the role of uncertainty management, robustness and flexibility should be further explored in SAM-related decisions. The inclusion of long-term perspectives and trends and perspectives such as sustainability, CE, and climate change require novel methods and criteria to be considered in decision-making. There is a need for methods that support SAM-related decision-making in situations where information on future development is uncertain and limited.

References

Aaheim, A. et al. (2013) Sector-level adaptation challenges in the literature. Deliverable 1.1. Available at: http://www.topdad.eu/upl/files/98434 (Accessed 24.6.2019).

AAMCoG (2012) Guide to integrated strategic asset management. Brisbane. Available at http://www.kmcgovern.com/wp-content/uploads/2012/07/AAMCOG_SAM_WEB_0312.pdf (Accessed 2.8.2019).

Adger, W. N., Arnell, N. W. and Tompkins, E. L. (2005) 'Successful adaptation to climate change across scales', Global Environmental Change 15(2), pp. 77-86. doi: 10.1016/j.gloenvcha.2004.12.005.

Adner, R. (2006) 'Match your innovation strategy to your innovation ecosystem', Harvard business review, 84(4), p. 98–107; 148.

Adner, R. and Kapoor, R. (2010) 'Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations', Strategic Management Journal. John Wiley & Sons, Ltd., 31(3), pp. 306–333. doi: 10.1002/smj.821.

Ahonen, T. et al. (2010) 'Maintenance communities - a new model for the networked delivery of maintenance services', International Journal of Business Innovation and Research, 4(6), pp. 560–583. doi: 10.1504/IJBIR.2010.035713.

Ahonen, T., Hanski, J. and Uusitalo, T. (2018) 'Approach to digital asset management se rvice development', in Proceedings of 13th World Congress on Engineering Asset Management (WCEAM2018). Presented at Stavanger, Norway on 24-26 September.

Åhrén, T. and Parida, A. (2009) 'Maintenance performance indicators (MPIs) for benchmarking the railway infrastructure', Benchmarking, 16(2), pp. 247-258. doi: 10.1108/14635770910948240.

Van Aken, J. E. and Romme, G. (2009) 'Reinventing the future: Adding design science to the repertoire of organization and management studies', Organisation Management Journal, 6(1) pp. 5-12. doi: 10.1057/omj.2009.1.

Alcamo, J. (2001) Scenarios as tools for international environmental assessments, October. European Environment Agency, Copenhagen. Available: https://www.eea.europa.eu/publications/environmental_issue_report_2001_24 (Accessed 2.8.2019). doi: 10.1080/00207720310001609039.

Almdal, W. (1994) 'Continuous improvement with the use of benchmarking', CIM Bulletin, 81(983), pp. 21-6.

Amadi-Echendu, J. E. et al. (2010) 'What is engineering asset management?', Engineering Asset Management Review, 1, pp. 3-16. doi: 10.1007/978-1-84996-178-3_1.

Amaratunga, D., Sarshar, M. and Baldry, D. (2002) 'Process improvement in facilities management: The SPICE approach', Business Process Management Journal, 8(4), pp. 318–337. doi: 10.1108/14637150210434982.

Andersen, K. and Terp, A. (2006) 'Risk Management', in Andersen, T. (ed.) Perspectives on Strategic Risk Management. Copenhagen Business School Press, pp. 27–46.

Andersen, T. J. and Schrøder, P. W. (2010) Strategic risk management practice: How to deal effectively with major corporate exposures. Cambridge University Press. doi: 10.1017/CBO9780511816017.

Asiedu, Y. and Gu, P. (1998) 'Product life cycle cost analysis: State of the art review', International Journal of Production Research, 36, pp. 883–908. doi: 10.1080/002075498193444.

Attwater, A. et al. (2014) 'Measuring the performance of asset management systems', in IET

Conference Proceedings Stevenage: The Institution of Engineering & Technology. London, UK. doi: 10.1049/cp.2014.1046.

AWWARF (2001) Financial and Economic Optimization of Water Main Replacement Programs. Denver.

Baines, T. and Lightfoot, H. W. (2014) 'Servitization of the manufacturing firm: Exploring the operations practices and technologies that deliver advanced services', International Journal of Operations and Production Management, 34(1), pp. 2-35. doi: 10.1108/IJOPM-02-2012-0086.

Baines, T. S. et al. (2007) 'State-of-the-art in product-service systems', Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 221, pp. 1543-1552. doi: 10.1243/09544054JEM858.

Barney, J. (1991) 'Firm Resources and Sustained Competitive Advantage', Journal of Management, 17(1), pp. 99–120. doi: 10.1177/014920639101700108.

Bauer, J. M. and Herder, P. M. (2009) 'Designing Socio-Technical Systems', in Philosophy of Technology and Engineering Sciences, 601-630. doi: 10.1016/B978-0-444-51667-1.50026-4.

Berkhout, F. et al. (2014) 'Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments', Regional Environmental Change, 14(3), pp. 879-893. doi: 10.1007/s10113-013-0519-2.

Bocken, N. M. P. et al. (2016) 'Product design and business model strategies for a circular economy', Journal of Industrial and Production Engineering, 33(5), pp. 308–320. doi: 10.1080/21681015.2016.1172124.

Boehm, M. and Thomas, O. (2013) 'Looking beyond the rim of one's teacup: A multidisciplinary literature review of Product-Service Systems in Information Systems, Business Management, and Engineering & Design', Journal of Cleaner Production, 51(15 July 2013), pp. 245-260. doi: 10.1016/j.jclepro.2013.01.019.

Braadbaart, O. (2007) 'Collaborative benchmarking, transparency and performance evidence from the Netherlands water supply industry', Benchmarking: An International Journal, 12(6), pp. 677-92. doi: 10.1108/14635770710834482.

Brimfield, B. E. and Myers, S. D. (2011) 'An integrated approach to benefits realisation of railway condition monitoring innovations', 5th IET Conference on Railway Condition Monitoring and Non-Destructive Testing (RCM 2011). doi: 10.1049/cp.2011.0577.

Brown, K. et al. (2014) 'An Integrated Approach to Strategic Asset Management', in Gheorghe, A. V, Masera, M., and Katina, P. F. (eds) Infranomics: Sustainability, Engineering Design and Governance. Cham: Springer International Publishing, pp. 57–74. doi: 10.1007/978-3-319-02493-6_5.

Brown, R. E. (2010) Business Essentials for Utility Engineers. 1st edn. Florida: CRC.

Brown, R. E. and Humphrey, B. G. (2005) 'Asset management for transmission and distribution', Power and Energy Magazine, IEEE, 3(June), pp. 39–45. doi: 10.1109/mpae.2005.1436499.

Brundtland, G. H. (1987) Our Common Future: Report of the World Commission on Environment and Development, United Nations Commission. doi: 10.1080/07488008808408783.

Bryman, A. and Bell, E. (2015) Business Research Methods -. 4th edn, Business Research Methods. 4th edn. Oxford Univesity Press.

Chemweno, P. et al. (2015) 'Asset maintenance maturity model: structured guide to maintenance process maturity', International Journal of Strategic Engineering Asset Management, 2(2), pp. 119–135. doi: 10.1504/IJSEAM.2015.070621.

Chen, M., Mao, S., and Liu, Y. (2014) 'Big data: a survey', Mobile Networks and Applications, 19, pp. 171–209. doi: https://doi.org/10.1007/s11036-013-0489-0.

Chesbrough, H. (2010) 'Business model innovation: Opportunities and barriers', Long Range Planning, 43(2-3), pp. 354-363. doi: 10.1016/j.lrp.2009.07.010.

Clark, D. N. (1997) 'Strategic management tool usage: a comparative study', Strategic Change, 6, pp. 417–427. doi: 10.1002/(SICI)1099-1697(199711)6:7<417::AID-JSC281>3.0.CO;2-9.

Clauss, T. (2017) 'Measuring business model innovation: conceptualization, scale development, and proof of performance', R&D Management, 47(3), pp. 385-403. doi: 10.1111/radm.12186.

Cook, D. J. et al. (1997) 'The relation between systematic reviews and practice guidelines', Annals of Internal Medicine, 127(3), pp. 210–216. doi: 10.7326/0003-4819-127-3-199708010-00006.

Coyne, I. T. (1997) 'Sampling in qualitative research. Purposeful and theoretical sampling; merging or clear boundaries?', Journal of Advanced Nursing, 26(3), pp. 623–630. doi: 10.1046/j.1365-2648.1997.t01-25-00999.x.

Creswell, J. W. (2014) Research Design : Qualitative, quantitative, and mixed methods approaches - 4th ed., SAGE Publication, Inc. doi: 10.1017/CBO9781107415324.004.

Cullen, W. (1990) Public inquiry into the Piper Alpha disaster. London: H.M. Stationery Office.

Da Xu, L., He, W. and Li, S. (2014) 'Internet of things in industries: A survey' IEEE Transactions on industrial informatics, 10(4), pp. 2233-2243. doi: 10.1109/TII.2014.2300753.

David, F. R. (2011) Strategic Management: Concepts and Cases. 13th edn. Pearson. doi: 10.1007/BF00292236.

Dessler, A. and Parson, E. (2005) The science and politics of global climate change: a guide to the debate. Cambridge: Cambridge University Press. doi: https://doi.org/10.1017/CBO9780511790430.

Dowlatshahi, S. (1992) 'Product design in a concurrent engineering environment: An optimization approach', International Journal of Production Research, 30(8), pp. 1803–1818. doi: 10.1080/00207549208948123.

Doz, Y. and Kosonen, M. (2008) Fast Strategy: How strategic agility will help you stay ahead of the game. FT Press.

Drucker, P. F. (1954) The practice of management, Business Horizons.

Easterby-Smith, M. et al. (2013) Management research, Sage. doi: 10.1097/01.brs.0000207258.80129.03.

EC (2013) Adapting infrastructure to climate change. European Commission staff working document. Available at: https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/swd_2013_137_en.pdf.

El-Akruti, K., Dwight, R. and Zhang, T. (2013) 'The strategic role of Engineering Asset Management', International Journal of Production Economics, 146(1), pp. 227-239. doi: 10.1016/j.ijpe.2013.07.002.

Elkington, J. (1998) 'Cannibals with forks: The triple bottom line of sustainability', New Society Publishers. doi: 10.1002/tqem.3310080106.

Ellen MacArthur Foundation (2016) 'Intelligent Assets: Unlocking the Circular Economy Potential', Ellen MacArthur Foundation, pp. 1–25. Available at: http://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Intelligent_Assets_080216.pdf.

Ellen MacArthur Foundation, SUN and McKinsey Center for Business and Environment (2015)

Europe's circular-economy opportunity, Report. Available at: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/europes-circular-economy-opportunity.

Ellram, L. M. (1995) 'Total cost of ownership', International Journal of Physical Distribution & Logistics Management, 25(8), pp. 4–23. doi: 10.1108/09600039510099928.

EN (2017a) EN 50126-1:2017 Railway Applications. The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS). Generic RAMS Process. European standard.

EN (2017b) Maintenance. Maintenance terminology, European Standard, SFS EN 13306:2017.

Epstein, M. J. (2008) Making Sustainability Work: Best Practices in Managing and Measuring Corporate Social, Environmental, and Economic Impacts. Sheffield, UK: Greenleaf.

Epstein, M. J. and Roy, M.-J. (2003) 'Improving Sustainability Performance Specifying Implementing and Measuring Key Principles', Journal of General Management. doi: https://doi.org/10.1177/030630700302900101.

Finger, M., Groenewegen, J. and Künneke, R. (2005) 'The Quest for Coherence between Institutions and Technologies in Infrastructures', Competition and Regulation in Network Industries, 6(4), pp. 227-259. doi: 10.1177/178359170500600402.

Fischer, C. and Gregor, S. (2011) 'Forms of reasoning in the design science research process', in Jain, H., Sinha, A., and Vitharana, P. (eds) Service-Oriented Perspectives in Design Science Research Lecture Notes in Computer Science (LNCS). Springer, pp. 17–32. doi: 10.1007/978-3-642-20633-7_2.

Fritsch, O. (2017) 'Integrated and adaptive water resources management: exploring public participation in the UK', Regional Environmental Change, 17(7), pp. 1933–1944. doi: 10.1007/s10113-016-0973-8.

Gartner (2018) IT Glossary. Available at: https://www.gartner.com/it-glossary/digitalization/ (Accessed: 12 July 2018).

Gartner (2012) Magic Quadrant for BI platforms. Analytics Value Escalator.

Geissdoerfer, M. et al. (2017) 'The Circular Economy – A new sustainability paradigm?', Journal of Cleaner Production, 143 (1 February 2017), pp. 757-768. doi: 10.1016/j.jclepro.2016.12.048.

Gill, T. and Hevner, A. (2013) 'A fitness-utility model for design science research', ACM Transactions on Management Information Systems (TMIS), 4(2), p. 5. doi: 10.1145/2499962.2499963.

Gregg, D. G., Kulkarni, U. R. and Vinzé, A. S. (2001) 'Understanding the Philosophical Underpinnings of Software Engineering Research in Information Systems', Information Systems Frontiers, 3(2), pp. 169–183. doi: 10.1023/A:1011491322406.

Grigg, N. S. (2005) 'Assessment and renewal of water distribution systems', Journal of American Water Works Association, 97(2), pp. 58–68. doi: 10.1002/j.1551-8833.2005.tb10825.x.

Haider, A. (2012) 'Information and Operational Technologies Governance Framework for Engineering Asset Management', Engineering Asset Management and Infrastructure Sustainability, pp. 299–313. doi: 10.1007/978-0-85729-493-7.

Hall, J. W. et al. (2004) 'A decision-support methodology for performance-based asset management', Civil Engineering and Environmental Systems, 21(1), pp. 51–75. doi: 10.1080/1028660031000135086.

Hamilton, M. C. et al. (2013) 'Case studies of scenario analysis for adaptive management of natural resource and infrastructure systems', Environmental Systems & Decisions, 33, p. 8. doi: 10.1007/s10669-012-9424-3.

Hanski, J., Keränen, J. and Molarius, R. (2018) 'Tools and Methods for Supporting Regional Decision-Making in Relation to Climate Risks', in Amini, A. (ed.) Climate Change and Global Warming. IntechOpen. doi: 10.5772/intechopen.80322.

Hanski, J., Kortelainen, H. and Uusitalo, T. (2018) 'The impact of digitalization on product-service system development in the manufacturing industry', in Proceedings of 13th World Congress on Engineering Asset Management (WCEAM2018). Presented at Stavanger, Norway on 24-26 September.

Hanski, J., Rosqvist, T. and Crawford-Brown, D. (2015) Demonstration description - visualisation of robust adaptation strategies. Available at: http://www.topdad.eu/upl/files/117029.

Hanski, J. and Valkokari, P. (2018) 'Impact of circular economy on asset management – lifecycle management perspective', in Proceedings of 13th World Congress on Engineering Asset Management (WCEAM2018). Presented at Stavanger, Norway on 24-26 September.

Harpur, P. and Brown, K. (2012) 'Contracting and Asset Management: Establishing an Asset Specificity Framework for Determining the Optimal Management of Tourism Infrastructure', in Mathew, J. et al. (eds) Engineering Asset Management and Infrastructure Sustainability. Springer, London, pp. 329–336. doi: 10.1007/978-0-85729-493-7.

Hastings, N. A. J. (2010) Physical asset management, Physical Asset Management. doi: 10.1007/978-1-84882-751-6.

Van der Heijden, K. (1996) The art of strategic conversation. John Wiley & Sons, Ltd. doi: 10.1038/sj.jors.2600027.

Herder, P. M. and Wijnia, Y. (2012) 'A systems view on infrastructure asset management', in Asset Management: The State of the Art in Europe from a Life Cycle Perspective, pp. 31–46. doi: 10.1007/978-94-007-2724-3_3.

Hevner, A. R. et al. (2004) 'Design Science in Information Systems Research', MIS Quarterly, 28(1), pp. 75–105. doi: 10.2307/25148625.

Hinkel, J. and Bisaro, A. (2016) 'Methodological choices in solution-oriented adaptation research: a diagnostic framework', Regional Environmental Change, 16(1), pp. 7–20. doi: 10.1007/s10113-014-0682-0.

Hirsjärvi, S., Remes, P. and Sajavaara, P. (2014) Tutki ja kirjoita. 19th edn. Helsinki: Tammi.

Hodkiewicz, M. (2015) 'Asset management - quo vadis (where are you going)?', International Journal of Strategic Engineering Asset Management, 2(4), pp. 313–327. doi: 10.1504/IJSEAM.2015.075411.

Holmström, J., Ketokivi, M. and Hameri, A.-P. (2009) 'Bridging Practice and Theory: A Design Science Approach', Decision Science, 40(1), pp. 65–87. doi: 10.1111/j.1540-5915.2008.00221.x.

IAM (2004) PAS 55-1&2-2004 - Asset Management Part 1: Specification of the optimal management of physical infrastructure assets. Asset management Part 2: Guidelines for the application of PAS 55-1, British Standard Institution.

IAM (2008) PAS 55-1&2-2008 - Asset Management Part1: Specification for the optimized management of physical assets. Asset Management. Part 2: Guidelines for the application of PAS 55-1, British Standard Institution.

IEC (2010) IEC 31010:2010 Risk management -- Risk assessment techniques.

IEC (2014) IEC 60300-1: Dependability management – Part 1: Guidance for management and application. Geneva: International Electrotechnical Commission (IEC).

IPCC (2014) 'IPCC Fifth Assessment Synthesis Report-Climate Change 2014 Synthesis Report', IPCC

Fifth Assessment Synthesis Report-Climate Change 2014 Synthesis Report.

IPWEA (2006) International infrastructure management manual. Sydney.

ISO (2009) ISO Guide 73:2009 Risk management - Vocabulary.

ISO 26000 (2010) ISO 26000 Social responsibility.

ISO 31000 (2018) ISO 31000 Risk management. Guidelines.

ISO 55000-2 (2014) 'BS ISO 55000-2014 - Asset Management - Overview, principles and terminology', BSI.

Johnson, G., Scholes, K. and Whittington, R. (2008) Exploring Corporate Strategy. 8th Editio, Exploring Corporate Strategy. 8th Editio. Prentice Hall. doi: 10.1016/0142-694X(85)90029-8.

Jonker, M. (2010) Modernization of electricity networks: Exploring the interrelations between institutions and technology. TU Delft.

Jorna, R. J., Hadders, H. and Faber, N. (2009) 'Sustainability, Learning, Adaptation, and Knowledge Processing', in Knowledge Management and Organizational Learning, pp. 369-384. doi: 10.1007/978-1-4419-0011-1.

Juhanko, J. et al. (2015) 'Suomalainen teollinen internet – haasteesta mahdollisuudeksi: taustoittava kooste', ETLA Elinkeinoelämän tutkimuslaitos, ETLA Raportit.

Kabir, G., Sadiq, R. and Tesfamariam, S. (2014) 'A review of multi-criteria decision-making methods for infrastructure management', Structure and Infrastructure Engineering, 10(9), pp. 1176–1210. doi: 10.1080/15732479.2013.795978.

Kasanen, E., Lukka, K. and Siitonen, A. (1993) 'The constructive approach in management accounting research', Journal of Management Accounting Research, 5, pp. 243–264.

Kasprzyk, J. R. et al. (2013) 'Many objective robust decision making for complex environmental systems undergoing change', Environmental Modelling and Software, 42 (April 2013), pp. 55-71. doi: 10.1016/j.envsoft.2012.12.007.

Keeble, J. J., Topiol, S. and Berkeley, S. (2003) 'Using indicators to measure sustainability performance at a corporate and project level', Journal of Business Ethics, 44(2-3), pp. 149-158. doi: 10.1023/A:1023343614973.

Kekki, T. et al. (2008) Vesijohtomateriaalien vauriot ja käyttöikä Suomessa [Damages and service life of water pipeline materials], Vesi-instituutin julkaisuja 3.

Kelly, E. (2015) 'Introduction: Business ecosystems come of age', Deloitte Business Trends Series.

Kersley, T. and Sharp, A. (2014) 'The Asset Management Journey : A Case Study of Network Rail ' s Journey supported by an Excellence Model', IET Conference Proceedings Stevenage: The Institution of Engineering & Technology (Nov 27, 2014).

Kinnunen, S.-K. et al. (2017) 'A Framework for Creating Value from Fleet Data at Ecosystem Level', Management Systems in Production Engineering, 25(3), pp. 163–167. doi: 10.1515/mspe-2017-0024.

Komljenovic, D. et al. (2016) 'Risks of extreme and rare events in Asset Management', Safety Science. Elsevier, 88, pp. 129–145. doi: 10.1016/J.SSCI.2016.05.004.

Komonen, K., Kortelainen, H. and Räikkonen, M. (2006) 'An Asset Management Framework to Improve Longer Term Returns on Investments in the Capital Intensive Industries', in Engineering Asset Management, pp. 418–432. doi: 10.1007/978-1-84628-814-2_46.

Komonen, K., Kortelainen, H. and Räikkönen, M. (2012) 'Corporate asset management for industrial companies: An integrated business-driven approach', in Asset Management: The State of the Art in

Europe from a Life Cycle Perspective, pp. 47–63. doi: 10.1007/978-94-007-2724-3_4.

Komonen, K., Kunttu, S. and Ahonen, T. (2011) 'In search of the Best Practices in Maintenance - New Methods and Research Results', in Handbook 1st International Maintworld Congress. Helsinki: KP-Media Oy, pp. 166–177.

Korse, M. et al. (2016) 'Embedding the Circular Economy in Investment Decision-making for Capital Assets - A Business Case Framework', in Procedia CIRP 48, pp. 425–430. doi: 10.1016/j.procir.2016.04.087.

Kortelainen, H. et al. (2017a) Fleet service creation in business ecosystems - from data to decisions, VTT Technology 309. Espoo, Finland: VTT Technical Research Centre of Finland, Ltd. Available at: https://www.vtt.fi/inf/pdf/technology/2017/T309.pdf.

Kortelainen, H. et al. (2017b) 'Tapping the Value Potential of Extended Asset Services – Experiences from Finnish Companies', Management Systems in Production Engineering, 25(3), pp. 199–204. doi: 10.1515/mspe-2017-0029.

Kortelainen, S. (2011) Analysis of the sources of sustained competitive advantage: system dynamic approach. Acta Universitatis Lappeenrantaesis 421.

Kortschak, D. and Perrels, A. (2013) Opportunities for tool-assisted decision support. The cases for energy, transport and tourism. Available at: http://www.topdad.eu/upl/files/98433.

Koskinen, I., Alasuutari, P. and Peltonen, T. (2005) Laadulliset menetelmät kauppatieteissä. Vastapaino.

Kossiakoff, A. and Sweet, W. N. (2003) Systems Engineering Principles and Practice, Wiley series in systems engineering and management. doi: 10.1002/0471723630.ch13.

Kramer, K. and Peppelman, B. (2012) 'Building a risk-based asset management capability - a multi-year organisation development journey', in IET & IAM Asset Management Conference 2012. doi: 10.1049/cp.2012.1914.

Kunttu, S. et al. (2016) 'Data to Decision - Knowledge-Intensive Services for Asset Owners', in Proceedings of EuroMaintenance 2016. Athens, Greece.

Kunttu, S., Kortelainen, H. and Horn, S. (2017) 'Demonstrating value with benchmarking', Maintworld, 3, pp. 34–37.

Labuschagne, C., Brent, A. C. and Van Erck, R. P. G. (2005) 'Assessing the sustainability performances of industries', Journal of Cleaner Production, 13(4), pp. 373-385. doi: 10.1016/j.jclepro.2003.10.007.

Lackmann, J., Ernstberger, J. and Stich, M. (2012) 'Market Reactions to Increased Reliability of Sustainability Information', Journal of Business Ethics, 107(2), pp. 111-128. doi: 10.1007/s10551-011-1026-3.

Lacy, P. and Rutqvist, J. (2016) Waste to wealth: The circular economy advantage. doi: 10.1057/9781137530707.

Laue, M. et al. (2014) 'Integrated strategic asset management: Frameworks and dimensions', Topics in Safety, Risk, Reliability and Quality. doi: 10.1007/978-3-319-02493-6_6.

Lee, J., Bagheri, B. and Kao, H. A. (2015) 'A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems', Manufacturing Letters, 3, pp. 18–23. doi: 10.1016/j.mfglet.2014.12.001.

van der Lei, T., Wijnia, Y. C. and Herder, P. M. (2012) 'Towards an Asset Management Framework of Asset Characteristics, Asset Environment, Lifecycle Phases, and Management', in Engineering Asset Management and Infrastructure Sustainability. doi: 10.1007/978-0-85729-493-7.

Leidecker, J. K. and Bruno, A. V. (1984) 'Identifying and using critical success factors', Long Range

Planning, 17(1), pp. 23–32. doi: 10.1016/0024-6301(84)90163-8.

Lempert, R. J. et al. (2006) 'A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios', Management Science, 52(4). doi: 10.1287/mnsc.1050.0472.

Lempert, R. J. and Groves, D. G. (2010) 'Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west', Technological Forecasting and Social Change, 77(6), pp. 960-874. doi: 10.1016/j.techfore.2010.04.007.

Lerch, C. and Gotsch, M. (2015) 'Digitalized Product-Service Systems in Manufacturing Firms: A Case Study Analysis', Research-Technology Management, 58(5), pp. 45-52. doi: 10.5437/08956308X5805357.

Levitt, T. (1960) 'Marketing myopia', Harvard Business Review. doi: 10.1023/A.

Lewandowski, M. (2016) 'Designing the Business Models for Circular Economy — Towards the Conceptual Framework', Sustainability, 8(1), p. 43. doi: 10.3390/su8010043.

Linder, M. and Williander, M. (2017) 'Circular Business Model Innovation: Inherent Uncertainties', Business Strategy and the Environment, 26(2), pp. 182-196. doi: 10.1002/bse.1906.

Liyanage, J. P. (2007) 'Operations and maintenance performance in production and manufacturing assets: The sustainability perspective', Journal of Manufacturing Technology Management, 18(3), pp. 304-314. doi: 10.1108/17410380710730639.

Liyanage, J. P. (2012) 'Smart engineering assets through strategic integration: Seeing beyond the convention', in Asset Management: The State of the Art in Europe from a Life Cycle Perspective, pp. 11–28. doi: 10.1007/978-94-007-2724-3_2.

Liyanage, J. P. and Badurdeen, F. (2010) 'Strategies for integrating maintenance for sustainable manufacturing', Engineering Asset Lifecycle Management, pp. 308-315. doi: 10.1007/978-0-85729-320-6_36.

Lukka, K. (2006) 'Konstruktiivinen tutkimusote: luonne, prosessi ja arviointi', in Rolin, K., Kakkuri-Knuutila, M.-L., and Henttonen, E. (eds) Soveltava yhteiskuntatiede ja filosofia. Helsinki: Gaudeamus, pp. 111–133.

Lusch, R. F. and Nambisan, S. (2015) 'Service Innovation: A Service-Dominant Logic Perspective', MIS Quarterly, 39(1), pp. 155–175. doi: 10.25300/MISQ/2015/39.1.07.

Lutchman, R. (2006) Sustainable asset management: linking assets people and processes for results. DEStech Publications, Inc.

MacGillivray, B. H. et al. (2007) 'Benchmarking risk management within the international water utility sector. Part I: Design of a capability maturity methodology', Journal of Risk Research, 10(1), pp. 85–104. doi: 10.1080/13669870601011183.

MacGillivray, B. H. and Pollard, S. J. T. (2008) 'What can water utilities do to improve risk management within their business functions? An improved tool and application of process benchmarking', Environment International, 34(8), pp. 1120-1131. doi: 10.1016/j.envint.2008.04.004.

Mahmood, M. et al. (2015) 'A comparative study on asset management capability maturity models', International Journal of Strategic Engineering Asset Management, 2(4), pp. 328–347. doi: 10.1504/IJSEAM.2015.075412.

Maier, H. R. et al. (2016) 'An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together?', Environmental Modelling and Software, 81, pp. 154–164. doi: 10.1016/j.envsoft.2016.03.014.

Mangano, G. and de Marco, A. (2014) 'The role of maintenance and facility management in logistics:

A literature review', Facilities, 32(5/6), pp. 241-255. doi: 10.1108/F-08-2012-0065.

March, S. T. and Smith, G. F. (1995) 'Design and natural science research on information technology', Decision Support Systems, 15(4), pp. 251–266. doi: 10.1016/0167-9236(94)00041-2.

Marlow, D. et al. (2007) Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets. Alexandria, Va.

Marlow, D., Beale, D. and Burn, S. (2010) 'Linking asset management with sustainability: Views from the Australian sector', Journal AWWA, 102(1), pp. 56-67. doi: https://doi.org/10.1002/j.1551-8833.2010.tb10026.x.

Marlow, D. R. and Burn, S. (2008) 'Effective Use of Condition Assessment within Asset Management', Journal AWWA, 100(1), pp. 54-63. doi: https://doi.org/10.1002/j.1551-8833.2008.tb08129.x.

McAllister, R. R. J., McCrea, R. and Lubell, M. N. (2014) 'Policy networks, stakeholder interactions and climate adaptation in the region of South East Queensland, Australia', Regional Environmental Change, 14(2), pp. 527-539. doi: 10.1007/s10113-013-0489-4.

Mediation (2013) Mediation toolbox. Available at: http://www.mediation-project.eu/platform/tbox/cba.html (Accessed: 20-06-2018).

Medina-Oliva, G. et al. (2014) 'Predictive diagnosis based on a fleet-wide ontology approach', Knowledge-Based Systems, 68, pp. 40–57. doi: 10.1016/j.knosys.2013.12.020.

Mehairjan, R. P. Y. et al. (2012) 'Organisation-wide maintenance & inspection improvement plan: A dutch electricity & gas distribution network operators approach', in IET Conference Publications. doi: 10.1049/cp.2012.1912.

Mehairjan, R. P. Y. (2016) Risk Based Maintenance in Electricity Network Organisations. TU Delft. doi: 978-94-028-0063-0.

Mileham, A. R. et al. (1993) 'A parametric approach to cost estimating at the conceptual stage of design', Journal of Engineering Design, 4(2), pp. 117–125. doi: 10.1080/09544829308914776.

Molarius, R. et al. (2008) Testing a Flood Protection Case by Means of a Group Decision Support System. VATT Discussion Papers 449.

Moon, F. et al. (2009) 'Governing issues and alternate resolutions for a highway transportation agency's transition to asset management', Structure and Infrastructure Engineering, 5(1), pp. 25-39. doi: 10.1080/15732470701322768.

Muntermann, J. (2009) 'Towards ubiquitous information supply for individual investors: A decision support system design', Decision Support Systems, 47(2), pp. 82–92. doi: 10.1016/j.dss.2009.01.003.

Ness, D. A. and Xing, K. (2017) 'Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model', Journal of Industrial Ecology, 21(3), pp. 572–592. doi: 10.1111/jiec.12586.

Nieboer, N. (2005) 'How strategic is asset management of institutional real estate investors?', Property Management, 23(1), pp. 22-32. doi: 10.1108/02637470510580561.

Niekamp, S. et al. (2015) 'A multi-criteria decision support framework for sustainable asset management and challenges in its application', Journal of Industrial and Production Engineering, 32(1), pp. 23–36. doi: 10.1080/21681015.2014.1000401.

Nielsen, D., Chattopadhyay, G. and Raman, D. (2013) 'An Australian railway bridge management framework', International Journal of Strategic Engineering Asset Management, 1(3), pp. 301–315. doi: https://doi.org/10.1504/IJSEAM.2013.056324.

OECD (2015) OECD Digital Economy Outlook. Paris: OECD Publishing. doi:

http://dx.doi.org/10.1787/9789264232440-8-en.

Ojanen, V. et al. (2012) 'Towards availability and sustainability in customer value assessment of asset management services', International Journal of Innovation and Sustainable Development, 6(4), pp. 368–391. doi: 10.1504/IJISD.2012.050866.

Osterwalder, A. and Pigneur, Y. (2010) Business Model Generation, A Handbook for Visionaries, Game Changers, and Challengers. doi: 10.1523/JNEUROSCI.0307-10.2010.

Ouertani, M. Z., Parlikad, A. K. and McFarlane, D. (2008) 'Asset information management: Research challenges', in Proceedings of the 2nd International Conference on Research Challenges in Information Science, RCIS 2008, pp. 361–370. doi: 10.1109/RCIS.2008.4632126.

Parida, A. (2012) 'Asset performance assessment', in Van der Lei, T., Herder, P., and Wijnia, Y. (eds) Asset Management: The State of the Art in Europe from a Life Cycle Perspective. Springer, pp. 101–113. doi: 10.1007/978-94-007-2724-3_7.

Parida, A. et al. (2015) 'Performance measurement and management for maintenance: A literature review', Journal of Quality in Maintenance Engineering, 21(1), pp. 2–33. doi: 10.1108/JQME-10-2013-0067.

Patton, M. Q. (1987) How to use qualitative methods in evaluation. Newbury Park, CA: Sage. doi: 10.1017/CBO9781107415324.004.

Peffers, K. et al. (2007) 'A Design Science Research Methodology for Information Systems Research', Journal of Management Information Systems, 24(3), pp. 45–77. doi: 10.2307/40398896.

Piirainen, K. and Gonzalez, R. (2013) 'Constructive Synergy in Design Science Research: A Comparative Analysis of Design Science Research and the Constructive Research Approach', Nordic journal of Business, 3–4, pp. 206–234. doi: 10.1007/978-3-642-38827-9_5.

Porter, M. E. (1985) Competitive Advantage: Creating and sustaining superior performance. New York: Free Press. doi: 10.1182/blood-2005-11-4354.

Porter, M. E. and Heppelmann, J. E. (2014) 'How Smart, Connected Product Are Transforming Competition', Harvard Business Review, November 2. doi: 10.1017/CBO9781107415324.004.

Porthin, M. et al. (2013) 'Multi-criteria decision analysis in adaptation decision-making: A flood case study in Finland', Regional Environmental Change, 13(6), pp. 1171–1180. doi: 10.1007/s10113-013-0423-9.

Povey, D. and Peach, N. (2013) 'Understanding and implementing strategic asset management at the University of Southern Queensland', Facilities, 31(7/8), pp. 343–356. doi: 10.1108/02632771311317484.

Raynor, M. (2007) The Strategy Paradox: Why Committing to Success Leads to Failure (And What to do About It). Crown Business.

Refsgaard, J. C. et al. (2007) 'Uncertainty in the environmental modelling process - A framework and guidance', Environmental Modelling and Software, 22(11), pp. 1543–1556. doi: 10.1016/j.envsoft.2007.02.004.

Rekola, K. and Haapio, H. (2009) Industrial Services and Service Contracts: A Proactive Approach. Helsinki: The Federation of Finnish Technology Industries.

Remenyi, D. et al. (1998) Doing research in business and management. London: Sage.

Ritala, P., Almpanopoulou, A. and Blomqvist, K. (2017) 'Innovation ecosystem emergence barriers: Institutional perspective', in The Proceedings of The 2017 ISPIM Forum, Toronto, Canada, 19-22 March 2017.

Rzevski, G. and Skobelev, P. (2014) Managing Complexity. WIT Press, Billerica, MA 01821, USA.

Salo, A. and Hämäläinen, R. P. (2010) 'Multicriteria Decision Analysis in Group Decision Processes', in Kilgour, D. M. and Eden, C. (eds) Handbook of Group Decision and Negotiation. Dordrecht: Springer Netherlands, pp. 269–283. doi: 10.1007/978-90-481-9097-3_16.

Salonen, A. and Bengtsson, M. (2011) 'The potential in strategic maintenance development', Journal of Quality in Maintenance Engineering, 17(4), pp. 337-350. doi: 10.1108/13552511111180168.

Saunders, M., Lewis, P. and Thornhill, A. (2016) Research Methods for Business Students. 7th edn, Research methods for business students. 7th edn. Pearson Education Limited. doi: 10.1017/CBO9781107415324.004.

Schaltegger, S. and Wagner, M. (2006) Managing the business case for sustainability. The integration of social, environmental and economic performance. Sheffield, UK: Greenleaf.

Schraven, D., Hartmann, A. and Dewulf, G. (2011) 'Effectiveness of infrastructure asset management: Challenges for public agencies', Built Environment Project and Asset Management, 1(1), pp. 61–74. doi: 10.1108/20441241111143786.

Scrieciu, S. Ş. et al. (2014) 'Advancing methodological thinking and practice for development-compatible climate policy planning', Mitigation and Adaptation Strategies for Global Change, 19(3), pp. 261–288. doi: 10.1007/s11027-013-9538-z.

de Senzi Zancul, E. et al. (2016) 'Business process support for IoT based product-service systems (PSS)', Business Process Management Journal, 22(2), pp. 305–323. doi: 10.1108/BPMJ-05-2015-0078.

Simon, H. A. (1997) The sciences of the artificial. 3rd edn, MIT Press. 3rd edn. Cambridge, MA. doi: 10.1016/S0898-1221(97)82941-0.

Snowden, D. J. and Boone, M. E. (2007) 'A leader's framework for decision making', Harvard Business Review, November. doi: 10.1109/MCDM.2007.369449.

Sommer, A. (2012) Managing Green Business Model Transformations. Springer Verlag.

Stahel, W. R. (2016) 'The circular economy', Nature, 23 March. doi: 10.1038/531435a.

Stapelberg, R. (2012) 'Research into Infrastructure Systems Vulnerability, Risk Exposure, and Sustainable Adaptive Capacity to Hazardous Conditions', in Mathew, J. et al. (eds) Engineering Asset Management and Infrastructure Sustainability. Springer-Verlag London Limited, pp. 865–883. doi: https://doi.org/10.1007/978-0-85729-493-7.

Sun, Y., Fidge, C. and Ma, L. (2009) 'A generic split process model for asset management decision-making', in Jinji, G. et al. (eds) Proceedings of the 3rd World Congress on Engineering Asset Management and Intelligent Maintenance Systems Conference (WCEAM-IMS 2008), 27 - 30 October 2008. China, Beijing.

Sun, Y., Ma, L. and Mathew, J. (2013) 'Improving asset management process modelling and integration', in Engineering Asset Management Review, pp. 71–87. doi: 10.1007/978-1-4471-2924-0_3.

Swart, R. et al. (2009) Europe adapts to climate change: Comparing national adaptation strategies. Partnership for European Research. PEER Report 1.

Thissen, W. et al. (2017) 'Dealing with Uncertainties in Fresh Water Supply: Experiences in the Netherlands', Water Resources Management, 31(2), pp. 703-725. doi: 10.1007/s11269-015-1198-1.

Tiusanen, R. and Jännes, J. (2017) 'Techno-economical evaluation of operating concepts in novel mobile machinery systems', in Proceedings of Automaatiopäivät 2017 Seminar.

Too, E. G. (2012) 'Strategic Infrastructure Asset Management: The Way Forward', in Engineering

Asset Management and Infrastructure Sustainability. doi: 10.1007/978-0-85729-493-7_73.

Toth, F. L. and Hizsnyik, E. (2008) 'Managing the inconceivable: Participatory assessments of impacts and responses to extreme climate change', Climatic Change, 91(1–2), pp. 81–101. doi: 10.1007/s10584-008-9425-x.

Tranfield, D., Denyer, D. and Smart, P. (2003) 'Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review', British Journal of Management, 14(3), pp. 207–222. doi: 10.1111/1467-8551.00375.

Triantis, A. J. (2003) 'Real Options', in Logue, D. and Seward, J. (eds) Handbook of Modern Finance. New York: Research Institute of America, pp. D1–D32.

Tsang, A. H. C., Jardine, A. K. S. and Kolodny, H. (1999) 'Measuring maintenance performance: A holistic approach', International Journal of Operations and Production Management, 19(7), pp. 691–715. doi: 10.1108/01443579910271674.

Tucker, M. and Pitt, M. (2009) 'Customer performance measurement in facilities management: A strategic approach', International Journal of Productivity and Performance Management, 58(5), pp. 407–422. doi: 10.1108/17410400910965698.

Tura, N. et al. (2019) 'Unlocking circular business: a framework of barriers and drivers', Journal of Cleaner Production, 212, pp. 90–98. doi: https://doi.org/10.1016/j.jclepro.2018.11.202.

UNFCCC (2010) Potential costs and benefits of adaptation options : A review of existing literature, United Nations Framework Convention on Climate Change (UNFCCC). Technical paper FCCC/TP/2009/2/Rev.1.

Uusitalo, T. et al. (2014) 'Support for Life Cycle Decision-Making in Sustainable Manufacturing: Results of an Industrial Case Study', in Advances in Production Management Systems: Innovative and Knowledge-Based Production Management in a Global-Local World. IFIP Advances in Information and Communication Technology; No. 439. Springer, p. Part II, 162-169. doi: 10.1007/978-3-662-44736-9.

Vaishnavi, V. and Kuechler, W. (2004) Design science research in information systems. Available at: http://www.desrist.org/design-research-in-information-systems/ (Accessed: 14 November 2018).

Vargo, S. L. and Lusch, R. F. (2011) 'It's all B2B...and beyond: Toward a systems perspective of the market', Industrial Marketing Management, 40, pp. 181–187. doi: 10.1016/j.indmarman.2010.06.026.

Verbruggen, A. (2013) 'Revocability and reversibility in societal decision-making', Ecological Economics, 85, pp. 21–27. doi: 10.1016/j.ecolecon.2012.10.011.

Volker, L. et al. (2014) 'Asset management maturity in public infrastructure: the case of Rijkswaterstaat', International Journal of Strategic Engineering Asset Management, 1(4), pp. 439–453. doi: 10.1504/IJSEAM.2013.060469.

Waeyenbergh, G. and Pintelon, L. (2002) 'A framework for maintenance concept development', International Journal of Production Economics, 77(3), pp. 299–313. doi: 10.1016/S0925-5273(01)00156-6.

WEF (2015) Industrial Internet of Things : Unleashing the Potential of Connected Products and Services. World Economic Forum (WEF). doi: 10.1111/hcre.12119.

Weick, K. E. and Sutcliffe, K. M. (2001) Managing the Unexpected: Resilient Performance in an Age of Uncertainty, Managing the Unexpected: Assuring High Performance in an Age of Complexity. Jossey-Bass. doi: 10.1108/ws.2002.07951dae.003.

Wernerfelt, B. (1984) 'A resource-based view of the firm', Strategic Management Journal, 5(2), pp. 171–180. doi: 10.1002/smj.4250050207.

Whateley, S., Steinschneider, S. and Brown, C. (2014) 'A climate change range-based method for estimating robustness for water resources supply', Water Resources Research, 50, pp. 8944–8961. doi: 10.1002/2014WR015956.

Wijkman, A. and Skånberg, K. (2015) The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency, The Club of Rome.

Wijnia, Y. C. (2016) Processing Risk in Asset Management. TU Delft.

Wijnia, Y. C. and Herder, P. M. (2010) 'The state of Asset Management in the Netherlands', in Engineering Asset Lifecycle Management SE - 19, pp. 164–172. doi: 10.1007/978-0-85729-320-6_19.

Woodhouse, J. (2003) 'Asset Management: latest thinking', in ICAMM 2003—international conference on asset and maintenance management. University of Pretoria.

Woodhouse, J. (2006) 'Putting the total jigsaw puzzle together: PAS 55 standard for the integrated, optimised management assets', in IMC-2006 the 21st international maintenance conference 2006. Daytona Beach, Florida.

Woodhouse, J. (2014) 'Asset Management is Growing up', in Tutorial at the 9th WCEAM, Pretoria.

Yin, R. K. (2003) Case Study Research: design and methods. 3rd edn, Case Study Research: design and methods. 3rd edn. Sage, Thousand Oaks (CA).

Younis, R. and Knight, M. A. (2014) 'Development and implementation of an asset management framework for wastewater collection networks', Tunnelling and Underground Space Technology, 39, pp. 130–143. doi: 10.1016/j.tust.2012.09.007.

Publication I

Hanski, J., Jännes, J., Valkokari, P., and Ojanen, V.
Strategic asset information management: Experiences from Finnish companies

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Strategic asset information management: experiences from Finnish companies

Jyri Hanski[1], Jere Jännes[1], Ville Ojanen[2], Pasi Valkokari[1]

Decisions on strategic asset management are crucial from the perspective of improving the sustainability of companies. The new ISO 55000 series of AM standards is a means of improving the AM strategies and practices of companies, and thus their sustainability performance. For this study, three Finnish companies were interviewed about their asset management, especially related to their asset information management practices and sustainability. The results are compared with the asset information management guidelines given in the AM standard. The goal of the research is to find best practices and areas of improvement in asset information management, and thus to improve asset management related decision-making and the sustainability of companies.

All the interviewed companies gather and analyse data from their machinery and infrastructure and the analysis and utilization of asset related information is considered important. The economic perspective of AM is seen crucial in decision-making, but also sustainability reporting, maintenance and operating information, value of assets and fault data are utilized. The asset information is scattered in different systems and behind different organisational barriers. Companies, however, strive towards unified asset information management systems.

1 Introduction

Strategic perspectives of asset management (AM) have earlier received less attention, but their importance at corporate level is increasing (Wilson 2002, Hastings 2009). Laue et al. (2014) argue that current AM related maturity models focus primarily on operational and technical level neglecting the strategy, policy, social and governance perspectives. Some dimensions of AM decisions have been based more on intuition and visions in comparison to structured and well-tooled analysis (Komonen et al. 2012). Brown et al. (2014) list the new issues that AM and AM models have to face i.e. sustainability, interaction between built assets and natural environment, resilience, life cycle management, community demands, information management and new types of governance arrangements. Production assets may have long life cycles and major changes occur in endogenous and exogenous factors during their life cycles. Thereby, decisions on strategic AM are crucial from the perspective of improving the sustainability of companies.

The new ISO 55000 (2014) series of AM standards is a means of improving the AM strategies and practices of companies, and thus their sustainability performance. The standard aims to represent the best practices of asset management worldwide. ISO 55000 (2014) defines AM as ”coordinated activities of an organization to realise value from assets”. Realised values are dependent on the goals, characteristics and objectives of the companies and its stakeholders. The standard emphasises the role, determines the central terms and concepts of AM and its interfaces to other activities of a company. It gives guidelines to creating and developing a sustainable AM system. Processes and strategies of information management are a central part of AM. The standard gives guidelines for management of asset information.

To improve the level of asset information management and sustainability in companies, there is a need for more information on their current level. Thus, the main research question of this study is as follows: ”What kind of asset

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management practices can be found in Finnish companies and how they compare with the guidelines of ISO 55000 series of AM standards?". The focus of research is especially on asset information management, strategic AM and sustainability. The goal of the research is to find best practices and areas of improvement in asset information management, and thus to improve asset management related decision-making and the sustainability of companies. For this study, three Finnish companies were interviewed about their AM, especially related to their asset information management practices. The results are compared with the asset information management guidelines given in the AM standard.

2 Methodology

The research is qualitative in nature and based on the results of interviews. Qualitative research methods were selected due to the newness of the research field. The research is based on six semi-structured interviews in three industrial companies. Altogether 14 persons were interviewed. The persons interviewed work in service, production or finance departments. Two companies were interviewed once and the third company four times in different business units. The interviews were recorded and transcripted. All of the companies are large Finnish companies with revenues of over 200 million euros. The interviews were aimed at finding the level of AM in the interviewed companies, focusing especially on their asset information management practices and strategies. The data was analysed by comparing it to the guidelines given in ISO 55000 series AM standard. Because of the limited number of the interviews, the data is mainly analysed as a whole, representing some of the best practices found in Finland.

3 Results

In this chapter, the results of the interviews are presented. The observations represent the opinions of the interviewees regarding AM and sustainability.

AM strategies and sustainability

The state of the interviewed companies' AM strategies and processes varies from several processes and strategies to no specific strategies in place or at least no strategies that the interviewees are aware of. In addition, there are departmental variations in the AM strategies inside the companies. There is an exchange of information with stakeholders, however the communication with customers is emphasised. Long-term relationships with customers are accentuated. Stakeholders are also communicated through sustainability reporting which increases the transparency of the companies. The need of consistency is stressed in management and reporting. Sustainability shows in the strategies in forms of energy efficiency demands, emissions monitoring and in selection and procurement of machinery and materials. Supplier selection may also include sustainability criteria. Production and environmental goals set standards for AM. Sustainability can also be seen in increased number of repairs and reduced number of replacements, and in new ways of inspections and acceptances. Moreover, often components are changed instead of replacing larger items such as equipment, modules, devices, etc.

Collecting AM related information

Data is collected from machinery and/or infrastructures in all the interviewed companies. Data collection has developed considerably with decreasing costs of instrumentation, development of data collection technologies and reduced number of people working at the facilities. The interviewed companies collect wide varieties of information depending on the type of the facility and the used components. For instance, process information, remote control and performance monitoring data, key performance indicators (KPI's), criticality ratings, storage information, asset values, lifetimes and estimates of replacement needs, production volumes, maintenance related information, authority reporting based data needs, waste and emissions, discharges, etc.

The collected information is also dependent on the fact if the company has service contracts with their clients. Clients might demand that the supplying companies bring new ideas to their AM processes. Reaching a holistic perspective on the impact mechanisms of particular systems is seen as a specific information need among some of the interviewees. There is no systematic quality control or standard for the information needs, apart from the quality standards set by the authorities for the authority reports. The goal of improving the quality of information is to prevent the disturbances in activities. Chaining of the utilisation of information and the lost connection to the original data are considered problems in quality control. Common information and information retrieval systems are considered a solution to this problem by the interviewees. Interviewed companies have methods and systems to support the various parts of information management process, for instance to support production, maintenance and process management. The most problematic areas related to the information management process are information standardisation and the end-of-life activities.

Analysis and utilisation of asset information

The information collected from machinery and infrastructure is analysed in the interviewed companies. The needs and wishes to the specification of the analysis are partly received from customer feedback questionnaires. Different energy efficiency and availability criteria and the fulfilment of quality criteria are followed especially. Other mentioned targets of analysis include machinery and component specific costs, asset value and cost per assets. Improvement in measuring technology helps information collection, analysis and utilisation. The management and ownership of the information infrastructure, for instance related to cloud services, is contemplated by the companies. Currently, the information is scattered in different systems. Data management is considered a problem, especially from the perspective of who can and has time to manage the data. Automated systems can already partly provide solution to this problem. The interviewees think that condition based maintenance is going to become more common as the measurement technology develops.

Utilisation of information is considered important. If the machinery or infrastructure is maintained at a right time, the lifetime costs are usually reduced. On the other hand, some maintenance activities can be performed less often when they are deemed less critical and move into real condition based maintenance. AM decisions need supportive reasoning, and purely statistics based decision support might not be good enough in industrial setting (in comparison with insurance companies). The interviewed companies mentioned examples of utilising the information, for instance reports made on the basis of the measurements and analyses and methods offered to the customer to utilise the produced information. AM information is used mainly on operational level, but it is also utilised to create the higher level performance indicators. In some cases, customer invoices ensure that the quality of the AM information is high enough for it to be sent it to the customers. Condition monitoring and process related measurement information are separated from the invoicing information and other information sources. All in all, the information used for invoices is better summarised but does not provide a holistic perspective on the level of AM, for instance the state of the critical components. In AM related decision-making the determining of the profitability of investments from the monetary perspective is crucial. However, also other types of information are used, for instance sustainability reporting, maintenance and operation information, value of assets and their depreciation, long-term maintenance programs, and failure and cost information.

AM risks, roles and responsibilities, processes, information exchange, and the quality and availability of information

The interviewed companies have identified the risks related to ownership and there are processes for risk management in place. The most important risks, their consequences and probabilities are listed. The demands from insurance companies are a major driver in charting the risks. Clients are also informed by the existence of risks and criticality assessments are made for them. A company assesses unavailability costs in different scenarios related to, for instance, capacity requirements, planned running times and usability. There has been a shift from reactive actions based on the results of the analyses to predicting risks and doing predictive actions. As an example of the changing mindset, the managers have the courage to make predictions about the machine failures on operational level. However, on the higher level there are deficiencies in assessing the significance of risks and in predicting the machinery and infrastructure failures. Local risk assessments are made on facility level to determine the critical components. Efficiency monitoring strives towards consideration of reasons and further measures, and understanding the figures instead of just reporting them.

AM roles and responsibilities are highly standardised, but some companies are aware of the need for clearer definitions to increase flexibility and improve work rotation. AM related maintenance responsibilities are defined in external customerships. AM processes and activities are described separately for each type of facilities, because of the different machinery and components. There is a considerable variance in information exchange with the most prominent stakeholders. Remote service systems enable the access to clients' information systems and, thus, make the information exchange easier. In this case, however, the confidentiality between the company and the client is crucial. Companies have plans for the communication with clients. Because of the customer driven approach to the business, the companies have less exchange of information with other stakeholders, but when it is necessary, it is described on project level. Companies gather information on its stakeholders through feedback, customer surveys and events. There are also some joint programs for, i.e., reducing the environmental impact of companies. In some of the companies the quality and availability of information and its meaning to support the company's decision-making is considered. They are conscious of the uncertainty and incompleteness of information. Their own assets are a source of reliable and accessible information. The operational environment is thought to be the challenging part of asset information management, even though it is considered at the corporate level. Risk charts are used to manage the risks of incomplete information.

4 Discussion

The guidelines given in the ISO 55000 (2014) series of standards are presented in *italics*. Conclusions based on the interview results follow the guidelines.

AM strategies and sustainability

Environmental, economic and social pillars of sustainability and the fulfilment of sustainability based organisational objectives are emphasised. The role of stakeholders and their requirements and expectations are also highlighted. Based on the characteristics and operational environment of the organisation, an organisation should create a strategic AM plan, which is consistent with organisational objectives. This plan sets criteria for AM decision-making. Different stakeholders may have conflicting objectives for AM from the sustainability perspective. Thus, the AM system should be transparent and consistent. (ISO 55000, 2014)

There are many developments that are increasing sustainability. However, AM strategies are not necessarily based on sustainable thinking, even though they might increase the sustainability of the company. The reasons behind this indirect improved sustainability include process development, energy and resource efficiency and the resulting cost savings or increased capacity. The role of stakeholders is emphasised. Customer is the most important stakeholder. Also government, society, suppliers and partners are mentioned. There is a big variation in the level of AM strategies and processes between and inside the companies. Sustainability reporting is practised in the companies. These indicators increase the transparency of AM systemand the consistency of its development.

Collecting AM related information

Requirements and the necessary information items are set for the information needs and the documentation of information. These include, for instance, user requirements, descriptions of assets and their purpose, various asset attributes, performance targets, key performance indicators, details of historical asset failures, etc. Information *needs of the organisation should be determined through a formalised approach to meet its organisational objectives. Value and quality of information should be taken into account relative to its costs and complexity of collecting, processing and managing. Availability of appropriate AM related information to assist in decision-making should be determined. Processes for collecting and managing asset information should be defined to ensure the accuracy, efficiency, traceability, auditability and timeliness of business processes and reporting. In addition, the methods for measurement and collection of source information, the frequency and verification of measurement, its storage and approval for further analysis should be defined. (ISO 55000, 2014.)*

Formalised approach for determining information needs was not found in the interviews. However, because of a limited number of interviews, there might be formalised approaches for determining information needs in place. Value and quality are taken into account and some problems in managing the information are recognised. Information collection is sometimes demanded by the clients. All the companies collect information from their assets. A wide variety of information is collected and it is used to support AM related decision-making. Methods and processes exist for collecting and managing asset information. For instance, customer feedback questionnaires, energy efficiency, and availability and quality criteria are followed. More holistic methods for AM might, however, be needed.

Analysis and utilisation of asset information

Organisation should define, implement and maintain the methods for analysis and evaluation of information, and processes for managing its information. There are differing information needs in different levels of organisation and a differing ability to have horizontal and vertical alignment of the information. Organisation should consider the complexity of its processes for managing its asset information. Asset related data can reside in many systems and, thus be very expensive to gather and maintain. Unnecessary duplication of data should be avoided and the data should reside in the most appropriate system. Processes for where and how the data is reworked into usable information and how it will be communicated should be defined. (ISO 55000, 2014)

The information collected from machinery and infrastructure is analysed in the interviewed companies. Purely statistical analysis is thought to be inadequate in industrial setting and is often complemented with condition based information. Based on the interviews, it would seem that there is a need for methods for the evaluation of information. The different levels of information have been recognised and some examples of alignment are found. A lot of information is produced but the state of critical components may not always be provided, because of the emphasis on the invoicing information. The companies have recognised the need for unified systems and the expensiveness of duplicating the data. Actions have been taken towards better asset data management.

AM risks, roles and responsibilities, processes, information exchange, and the quality and availability of information

The organisation should include consideration of the significance of the identified risks, the roles and responsibilities for AM, the AM processes, procedures and activities, exchange of information with its stakeholders, including service providers, and the impact of quality, availability and management of information on organizational decision making. Organisation should consider the need to align its information requirements to suit the level of risk that an asset poses. The information should be easily exchangeable with service providers. The use of common terminology increases understanding between stakeholders and inside the organisation. To ensure the completeness, accuracy and integrity of AM information, collaboration amongst relevant stakeholders is needed. There is a need for a quality of information that is relative to its use. (ISO 55000, 2014)

Processes for risk management are in place and the significance of identified risks is considered. The interviewees give some examples of predictive risk management. Risks related to ownership are identified and there are processes for risk management in place. There has been a shift from reactive actions based on the results of the analyses to predicting risks and doing predictive actions and managers have the courage to make predictions about the machine failures on operational level. On the higher level there are deficiencies in assessing the significance of risks and in predicting the machinery and infra failures. Local risk assessments are made on facility level to determine the critical components. It was not found out in interviews if the criticality of components affects the information requirements, but it should. All in all, the risk management is at a good level, even though there are development needs in corporate level asset risk assessment.

AM roles and responsibilities are highly standardised, but some improvement areas are recognised such as need for clearer definitions to increase flexibility and improve work rotation. AM related maintenance responsibilities are defined in external customerships. AM processes and activities are described separately for each type of facilities, because of the different machinery and components. Exchange of information is practised mainly with customers. There is a considerable variance in information exchange with the most prominent stakeholders (reasons: remote service systems, confidentiality). Companies gather information on its stakeholders through feedback, customer surveys and events. There are also some joint programs for, i.e., reducing the environmental impact of companies. Customer's role was emphasised in the interviews, however, also other stakeholders were taken into account. In some companies the impact of quality, availability and management of information on organisational decision-making is considered in the companies. The operational environment is thought to be the challenging part of asset information management, even though it is considered at the corporate level. Uncertainty of information is also considered and risk charts are used.

5 Conclusions

All the interviewed companies gather and analyse data from their machinery and infrastructure. However, data management is seen as a challenge. The analysis and utilization of asset related information is considered important. The economic perspective of AM is seen crucial in decision-making. Also sustainability reporting, maintenance and operating information, value of assets and fault data are utilized. Companies also help their value network to utilize the asset information better. The state of the interviewed companies' AM strategies and processes varies; some have several processes and strategies and some have no specific strategies in place or at least no strategies that the interviewees are aware of. At the moment, AM strategies are not necessarily based on sustainability, even though they might increase the sustainability of the companies. Process development, energy and resource efficiency, capacity increase and cost savings are the most important drivers behind the AM activities. The interviewed companies have all considerable asset base and benefit from sustainable strategic asset management practices.

Decision-making is still based on intuition, expert opinion and experience and the asset based information is used mainly on operational level. There are still several points of improvement in asset information management and information systems. AM related information is still scattered in many systems and controlled by various agents in the network. The companies are, however, aware of this and strive towards integrated information systems as presented in the ISO 55000 (2014) AM standard series. Integrated approach to the management systems enables the use of existing systems (quality, environmental, safety, etc. systems) and, thus, reduces the need of developing new systems. This development enables more sustainable AM systems to be developed.

Adopting sustainable development as a guideline can be considered as a strategic decision, especially if sustainability has not been a part of company's values before. To demonstrate the sustainability transparently, sustainability perspectives (environmental, social and economic) should be taken into account in the reporting and management of the company. The companies have recognised this and are striving towards a more sustainable future. AM strategies are in a key role when improving company's performance from the sustainability perspective. Sustainability of companies could be improved by using more AM based sustainability indicators, and using the asset information to support the decision-making more extensively. Emphasising sustainable development enables the companies to create new services and internally develop their processes and activities. Three proposals to improve the sustainability of the AM include (1) better linking the AM information to management systems, (2) predicting and visualising the development of the sustainability and AM indicators and (3) increasing transparency and the use of real time information. Further research is needed to determine the benefits of these suggestions.

References

Brown, K., Laue, M., Tafur, J., Mahmood, M.N., Scherrer, P., Keast, R. 2014. *An Integrated Approach to Strategic Asset Management*. In: Infranomics: Topics in Safety, Risk, Reliability and Quality Volume 24, 2014, pp 57-74.

Hastings, N. A. J. 2009. *Physical asset management*. Springer Science & Business Media.

ISO 55000 2014. *Asset management -- Overview, principles and terminology*.

ISO 55001 2014. *Asset management — Management systems — Requirements*.

ISO 55002 2014. *Management systems — Guidelines for the application of ISO 55001*.

Komonen, K., Kortelainen, H., Räikkönen, M. 2012. *Corporate asset management for industrial companies: an integrated business-driven approach*. In Asset management (pp. 47-63). Springer Netherlands.

Laue, M., Brown, K., Scherrer, P., Keast, R. 2014. *Integrated Strategic Asset Management: Frameworks and Dimensions*. In: Infranomics: Topics in Safety, Risk, Reliability and Quality Volume 24, 2014, pp 75-87.

Wilson, A. (Ed.). 2002. *Asset maintenance management: a guide to developing strategy & improving performance*. Industrial Press Inc.

Publication II

Hanski, J. and Ojanen, V.
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Circular economy models – opportunities and threats for asset management

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Circular economy models – opportunities and threats for asset management

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***Abstract*— Companies increasingly focus on their long-term sustainability and ecological footprint. Circular economy models are a step towards more sustainable business in networked companies. Majority of business models contain elements of circular economy. These models have implications for the asset management strategies, processes and practices in companies. They create new kinds of opportunities and threats and enable new asset management related innovations.**

In this paper, some of the existing circular economy models are presented. Two assessment frameworks are utilised to identify the different types of models. The circular economy models are analysed from the asset management perspective. The goal of this paper is to discuss the opportunities and threats produced by the circular economy models for asset management.

***Keywords*— Asset management, circular economy, threats, opportunities**

I. INTRODUCTION

Often, industrial processes and supply chains are understood and operated as a linear sequence such as extraction, transport, conversion, consumption, waste and disposal, or take, make and dispose (Schulte 2013, Ellen MacArthur Foundation 2015a). Linear supply chains are designed to improve the efficiency of each life cycle phase aiming to ensure maximum output at minimal cost. In such a system, returning or repairing products for reuse creates additional costs and forms a disturbance to the optimized flow. (Schulte 2013.)

In comparison, according to circular economic principles a product is designed to create minimal waste by for instance, allowing it to be easily repaired, or the materials or components to be upgraded or reused (Schulte 2013). Circular economy aims to be a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields, and minimises system risks by managing finite stocks and renewable flows (Ellen MacArthur Foundation 2015a). In circular models, value creation is built on longevity and new consumption forms (Schulte 2013).

The concept of circular economy is restorative and regenerative by design aiming to keep products, components, and materials at their highest utility and value at all times (Ellen MacArthur Foundation 2015a). Adoption of circular economy business models has been low (Sommer 2012, Linder and Williander 2015). Currently, companies have started to exploit untapped potential along the value chains and to promote resource and energy management concepts. Major global companies such as Google, Unilever and Renault have been recently paying attention to circular economy, however, it should concern also smaller companies that are increasingly affected by the shift to circular economy model (Lewandowski 2016). The evolution of companies toward the circular economy implies radical changes not only in their business and operating models, but also in the ensemble of their supply chains, partnerships and value networks. The challenge is how the companies can exploit the business opportunities resulting from the transition to a more sustainable economy.

A shift to circular economy is seen beneficial from the environmental and social perspectives but also from the economic standpoint. It is estimated that a shift to a circular economy would reduce each European nation's greenhouse-gas emissions by up to 70% and grow its workforce by about 4% (Wijkman and Skånberg 2015, Stahel 2016). Ellen MacArthur Foundation et al. (2015) present that adopting circular economy principles would, in addition to social and environmental benefits, generate a net economic benefit of 1.8 trillion € by 2030.

Circular economy has implications for the asset management strategies, processes and practices in companies. It creates new kinds of threats and opportunities and enables new asset management related innovations. Circular economy and asset management both aim at more efficient resource usage. Physical assets contain many scarce materials and thus, asset management is a key circular economy research area (Korse et al. 2016). All things considered, asset management has a major role in reaching the social, environmental and economic targets set to circular economy.

However, asset management literature has paid little attention to circular economy (Korse et al. 2016). There is a lack of guidance for taking sustainability aspects into account in asset management (Niekamp et al. 2015). Relation of circular economy principles and asset management is not defined clearly (Niekamp et al. 2015, Korse et al. 2016). Additionally, there is a lack of methods to support circular economy based asset management decisions (Korse et al. 2016). Many of the circular economy models presented in the literature discuss the role of asset management, its requirements and possible enablers and barriers only at a general level if at all. The special requirements for maintenance are also not considered. Circular economy examples mostly focus on the material flows between the producers and customers, while the information flows between the key stakeholders required to deliver, maintain and dispose the product or service are usually not covered.

In this study, we identify typical circular economy models and analyse them from the asset management perspective. In addition, we discuss the threats and opportunities produced by the circular economy models for asset management.

II. CIRCULAR ECONOMY MODELS

Several authors have provided classifications for circular economy business and operating models (e.g. Bocken et al. 2016, Lacy and Rutqvist 2015, Ellen MacArthur Foundation 2013). In this paper, we do not analyse the characteristics of these business or operating models. We present the classifications of Bocken et al. (2016) and Lacy and Rutqvist (2015) as these classifications are complementary and offer different perspectives to circular economy models i.e. sustainability and business perspectives respectively.

Bocken et al. (2016) divide circular economy strategies into three categories:

1. **Slowing resource loops**
2. **Closing resource loops**
3. **Resource efficiency or narrowing resource flows**

Firstly, slowing resource loops is achieved through designing long-life goods and extending product-life. Product-life can be extended through, for instance, repair and remanufacturing. The extension or intensification of product-life increases the utilization period of products and, thus, results in a slowdown of the flow of resources. For the slowing of resource loops, four circular economy models are introduced: access and performance model, extending product value, classic long-life model and encouraging sufficiency.

Secondly, closing resource loops is reached through recycling. In this archetype, the loop between post-use and production is closed resulting in a circular flow of resources. Two models for closing loops are presented: extending resource value and industrial symbiosis. Thirdly, resource efficiency or narrowing resource flows aims at using fewer resources per product.

Lacy and Rutqvist (2015) present a more business oriented view of circular economy models (A-E):

A. Circular supply-chain, where supply resources are designed for regeneration. In the circular supply chain fully renewable, recyclable or biodegradable inputs are used as substitutes for linear ones. Examples of products offered with business models belonging in this category are renewable energy, and bio-based and recyclable materials. These products can be produced for other companies or for own operations. Examples of companies using this business model type include CRAiLAR (biomass), Natureworks (biopolymers), AkzoNobel (paints and coatings) IKEA (producing and using renewable energy) and Ecovative (mushroom based plastics).

B. Recovery and recycling, where sources hiding in companies' production outputs and discarded products are protected, recaptured, and reused. The goal of this circular economy model is to find value in all material streams. Examples of companies using recovery and recycling model are General Motors (zero waste program), Interface (reuse nylon from fishnets in carpet manufacturing) and PUMA (bring me back bins).

C. Product life extension, where products that are built to last. The goal of this model is to increase the value from the invested resources and provide as long as possible useful life and maximized profitability over life cycle of products. Product life extension includes activities such as built to last, resell, repair, upgrade, refill, refurbish and remanufacture. Companies using product life extension approach include, for instance, Electrolux (modularity in products) and Caterpillar (remanufacturing).

D. Sharing platform, where the goal is to boost the productivity of assets. For instance, companies such as AirBnB, LiquidSpace and Lyft are utilizing this model. Sharing platform provides a means to connect product owners with individuals or companies that would like to use them.

E. Product as a service (PaaS), where performance is on focus over ownership. Unlike in sharing economy, companies retain ownership of a product and offer it to customers in a product-service system, PSS. Examples of companies using this circular economy model type include, for instance, Michelin (Stahel 2016).

Error! Reference source not found. introduces the connections between the taxonomies of Bocken et al. (2016) and Lacy and Rutqvist (2015).

TABLE I. CIRCULAR ECONOMY MODELS ANALYSED IN THIS STUDY.

Taxonomy of Lacy and Rutqvist (2015)	Taxonomy of Bocken et al. (2016)
A. circular supply-chain	2. closing resource loops
B. recovery and recycling	2. closing resource loops 3. resource efficiency or narrowing resource flows
C. product life extension	1. slowing resource loops 3. resource efficiency or narrowing resource flows
D. sharing platform	1. slowing resource loops 3. resource efficiency or narrowing resource flows
E. product as a service	3. resource efficiency or narrowing resource flows

III. ASSET MANAGEMENT AND CIRCULAR ECONOMY

Asset management can be defined as "coordinated activity of an organization to realize value from assets". Realization of value involves balancing of costs, risks, opportunities and performance benefits. (ISO 55000 2014.) This definition takes into account the increasing complexity, uncertainty and requirements that the asset managers have to face. Current industrial networks involve a number of organizations as key stakeholders including asset operators and owners, regulatory and statutory bodies, service providers, engineering contractors, technology developers, equipment manufacturers, spare part vendors and logistic providers (Liyanage 2012). Brown et al. (2014) list sustainability, interaction between built assets and natural environment, resilience, life cycle management, community demands, information management and new types of governance arrangements as issues that the current asset management systems need to take into account. On the whole, asset management systems contain multiple stakeholders and value elements that should be considered when making asset related decisions.

The effect of circular economy on asset management can be discussed through asset management fundamentals presented in ISO 55000 (2014):

- **Value**. The goal of asset management is to provide tangible or intangible value to the organisation. The value is determined by the organisation and its stakeholders so that it is aligned with the organisational objectives. Use of lifecycle approach is emphasised.

- **Alignment**. Organisational objectives are translated into technical and financial plans and decisions by asset management. Organisations should have risk-based and information-driven planning and decision-making processes, integration of asset and functional management processes (e.g. finance, human resources, information systems, logistics and operations) and the specification and implementation of supporting asset management system in place.

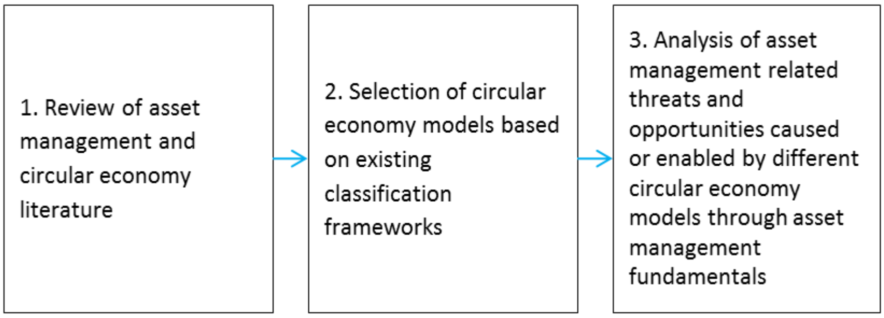
- **Leadership**. Leadership and workplace culture are elements determining the realization of value. Organisations should consider having clearly defined roles and responsibilities, ensuring that its employees are aware, competent, and empowered, and consulting with employees and stakeholders regarding asset management.

- **Assurance**. Asset management should give assurance that assets fulfil their required purpose. In order to fulfil the needs of assurance, organisations should implement processes for connecting the purposes and performance of the assets to the organizational objectives, for assurance of capability and for monitoring and continual improvement, and providing the necessary resources and competent personnel for demonstrating assurance.

IV. METHODOLOGY

Error! Reference source not found. presents the research methodology used in this study.

Fig. 1. Research methodology.



Firstly, asset management and circular economy literature is reviewed. Secondly, two assessment frameworks, Bocken et al. (2016) and Lacy and Rutqvist (2015), are identified and utilised to classify the different types of circular economy models. Thirdly, the models are analysed for the asset management related threats and opportunities. Asset management fundamentals described in ISO 55000 (2014) are used as a basis for the analysis. The evaluation of the opportunities and threats is conducted in a workshop in which the authors analyse the circular economy models one by one from the perspective of the asset management fundamentals. Examples of circular economy models were used to help to focus on the specific circular economy models. The evaluation is based on the expert opinion of the authors.

Firstly, asset management and circular economy literature is reviewed. Secondly, two assessment frameworks are identified and utilised to classify the different types of circular economy models. Thirdly, the models are analysed for the asset management related threats and opportunities. Asset management fundamentals described in ISO 55000 (2014) are used as a basis for the opportunity and threat evaluation. The evaluation of the opportunities and threats on based on expert opinion of the authors and an expert opinion workshop involving external specialists.

V. RESULTS

Circular economy models bring new opportunities and threats for asset management activities and processes in companies. In Table 2, the threats and opportunities for asset management fundamentals are presented. The fundamentals are divided into two categories; value and value supporting activities (alignment, leadership and assurance). The threats and opportunities are considered especially from the asset owner's perspective.

TABLE II. IMPLICATIONS OF CIRCULAR ECONOMY MODELS FOR ASSET MANAGEMENT.

Circular economy model	Threats	Opportunities
Circular supply-chain - closing resource loops **Example:** Production of biomaterials from the side streams of paper production	**Value** - Changing, new value elements → Communication of value to stakeholders is a challenge - Obsolescence of old assets **Alignment, leadership & assurance** - Increased system complexity → limited availability of information → challenges for decision-making - More actors and stakeholders in the value chain increase the complexity of organisation and cause new challenges for leadership and the assurance of performance - availability of information → stakeholders not necessarily known when designing ecosystems and preferable stakeholders cannot always be selected - biological contamination → same or better quality requirements as for nonbiological products (a challenge for producers)	**Value** - Secure the availability and protection from the price volatility of critical resources for production and delivery - New purposes for old assets **Alignment, leadership & assurance** - Demand for new asset management system is an opportunity for improved asset management system - New asset management system enables better leadership & assurance
Recovery and recycling - closing resource loops - resource efficiency or narrowing resource flows **Example:** Recycled paper production	**Value** - Recycled raw materials may cause disturbances to production machinery (e.g. contaminated materials and products) - Increased complexity of machinery fleet (new types of machinery needed) **Alignment, leadership & assurance** - Increased system complexity → limited availability of information → challenges for decision-making - More actors and stakeholders in the value chain increase the complexity of organisation and cause new challenges for leadership and the assurance of performance - Are the products produced from recycled materials as good as from virgin materials? - Unavailability of recycled raw material may lead to unplanned production stoppages → failures may occur during ramp-up	**Value** - new purposes for old assets **Alignment, leadership & assurance** - Demand for new asset management system is an opportunity for improved asset management system - New asset management system enables better leadership & assurance
Product life extension - slowing resource loops - resource efficiency or narrowing resource flows **Example:** Caterpillar's remanufacturing concept	**Value** - Performance of assets → Remanufacturing machinery that is obsolete from the economic perspective **Alignment, leadership & assurance** - Availability of information → better information of utilization, condition and location of machinery needed - How to assure that purpose is fulfilled? → can new features be built on old chassis? → how to implement assurance processes for new kind of life cycle phases?	**Value** - cost reduction → reduction of new materials and energy consumption in production **Alignment, leadership & assurance** - Demand better monitoring of performance of the product and the supporting processes to be successful → other benefits such as decreased failures and disturbances, new service opportunities and concepts
Sharing platform - slowing resource loops - resource efficiency or narrowing resource	**Value** - Large amount of different users → challenge for durability and asset management **Alignment, leadership & assurance** - Information need (location, condition, operational environment of the machine) → how to implement effectively supporting asset management system - How to assure that the asset fulfil the needs of	**Value** - More efficient use of resources (utilization rate) **Alignment, leadership & assurance** - Information need (location, condition, operational environment of the machine) → better availability of information - Demand better monitoring of use and performance to be successful → new service potential for increased customer value such as

flows **Example:** Concept for renting machinery and power tools (e.g. Cramo)	the user/customer?	decreased failures and disturbances through usage optimisation
Product as a service - resource efficiency or narrowing resource flows **Example:** Cost per performance concept (e.g. Rolls Royce)	**Value** - Up-front investment - Market risk **Alignment, leadership & assurance** - Distributed asset base a challenge for process alignment - Conflicting interests between customer and owner (market related reasons, other reasons) - Usage of machinery (different users and ways of use, owner cannot necessarily affect) - Information needs (location, condition etc.)	**Value** - Continuous steady income, predictability, less fluctuations - material flow is owned and managed by the producer **Alignment, leadership & assurance** - Closer customer relationship related to management of assets → increased capability to assure that assets fulfil their purpose

VI. CONCLUSIONS

Asset management objectives are derived from the strategic objectives of an organisation and aims at maintaining and improving the value of the asset base. When moving from linear operating models to circular models asset managers have to consider many new factors related to the asset management fundamentals presented in ISO 55000 (2014). However, the asset management literature has not yet paid attention to the changing requirements and needs of circular economy models. In fact, the circular economy has been paid little attention in the asset management literature (Korse et al. 2016). The goals of asset management and circular economy are at large aligned, as both aim at increased resource efficiency and prolonging the useful life of machinery.

In this paper, we identify asset management related threats and opportunities in circular economy models from the asset owner's perspective. Based on the analysis, the opportunities and threats for asset management are different in different circular economy models. In addition, they are different from the many generic circular economy the opportunities and threats identified in the literature (e.g. Mentink 2014). The circular economy models, in general, introduce asset management threats related to complexity of the supply chain and information systems, new value elements and their management and the assurance of quality in the new ecosystem. The opportunities for asset management include, for instance, potential for new purposes for the old equipment, potential for an improvement asset management system, and cost savings and quality improvements through better availability and quality of information.

This paper is our first attempt to assess the effect of asset management on the circular economy models and how the selection of a specific circular economy model affects the requirements for asset management. We argue that asset management is one of the most important factors to be considered when developing, implementing and using circular economy based business models.

Additionally, the goal of this study is to further develop the archetypes of circular economy models presented in this paper from the perspective of asset management. Depending on the examples and companies considered, the opportunities and threats for asset management change. In addition, some operating models that contain circular economy elements, such as virtualization and dematerialization, and producing on demand are not considered in these archetypes. Our goal is to create representative case examples that consider the information and material flows, as well as asset management perspectives. Ultimately, we aim at creating a new classification of circular economy models based on the asset management perspective. The cases and archetypes help companies and organisations to better assess and develop their processes and business models towards circular economy.

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REFERENCES

[1] Bocken NMP, de Pauw I, Bakker C, van der Grinten B (2016) Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33:5, pp. 308-320, DOI: 10.1080/21681015.2016.117212.

[2] Brown K, Laue M, Tafur J, Mahmood MN, Scherrer P, Keast R (2014) An Integrated Approach to Strategic Asset Management. In: Infranomics: Topics in Safety, Risk, Reliability and Quality Volume 24, 2014, pp 57-74.

[3] Ellen MacArthur Foundation (2015) Circular Economy Overview. Website of Ellen MacArthur Foundation. Available at: https://www.ellenmacarthurfoundation.org/circular-economy/overview/concept.

[4] Ellen MacArthur Foundation (2015b) Circular Economy Building Blocks. Website of Ellen MacArthur Foundation. Available at: https://www.ellenmacarthurfoundation.org/circular-economy/building-blocks.

[5] Ellen MacArthur Foundation (2013) Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. Report. Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.

[6] Ellen MacArthur Foundation, SUN and McKinsey Center for Business and Environment (2015) Europe's circular-economy opportunity. Report. Available at: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/europes-circular-economy-opportunity.

[7] ISO 55000 2014. Asset management. Overview, principles and terminology. Standard.

[8] Korse M, Ruitenburg RJ, Toxopeus ME, Braaksma AJJ (2016) Embedding the circular economy in investment decision-making for capital asset – a business case framework. Procedia CIRP 48, pp. 425-430.

[9] Lacy P, Rutqvist J (2015) Waste to Wealth: The Circular Economy Advantage. Palgrave Macmillan 2015.

[10] Lewandowski M (2016) Designing the Business Models for Circular Economy – Towards the Conceptual Framework. Sustainability, 8, 43.

[11] Linder M, Williander M (2015) Circular Business Model Innovation: Inherent Uncertainties. Business Strategy and the Environment. DOI: 10.1002/bse.

[12] Liyanage JP (2012) Smart Engineering Assets Through Strategic Integration: Seeing Beyond the Convention. In: van der Lei T, Herder P, Wijnia Y (2012) Asset Management – The State of the Art in Europe from a Life Cycle Perspective. Springer Netherlands.

[13] Mentink B (2014) Circular Business Model Innovation. Master's thesis, TU Delft.

[14] Niekamp S, Bharadwaj UR, Sadhukhan J, Chryssanthopoulos MK (2015) A multi-criteria decision support framework for sustainable asset management and challenges in its

application, Journal of Industrial and Production Engineering, 32:1, 23-36.

[15] Schulte U (2013) New business models for a radical change in resource efficiency. Environmental Innovation and Societal Transitions, Volume 9, Pages 43–47.

[16] Sommer A (2012) Managing Green Business Model Transformations. Dissertation. Springer Verlag.

[17] Stahel (2016). The circular economy. Nature 23 March 2016. Available at: http://www.nature.com/news/the-circular-economy-1.19594.

[18] Wijkman A, Skånberg K (2015) Circular Economy and Social Benefits: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency. A study report at the request of the Club of Rome with support from the MAVA Foundation.

Publication IV

Hanski, J., Luomanen, T., Kortelainen, H., and Välisalo, T.

Methods for value assessment of water and sewer pipelines

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Methods for Value Assessment of Water and Sewer Pipelines

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Abstract. *Assessing the value of physical assets is an important part of good asset management practices. The value of existing assets has become a factor of special interest to the asset owners as outsourcing of maintenance duties has increased. The value of water and sewer systems should also be assessed in order to follow up the development of the network's long-term condition during a maintenance partnership contract and to determine the optimal renovation timing and method. In addition, the deficiencies in assessing the value of the system are considered one of the main obstacles to wider application of private-public co-operation.*

There are no commonly accepted value assessment methods, at least not in Finland. Many factors affect the condition of the network, which makes the determination of the service life difficult. The use of existing value assessment methods is also essential in order to assess the systems economically. However, the value should be addressed holistically instead of determining only the economic value of the system.

In this paper, we provide a comprehensive discussion on the value assessment of the water and sewer systems. Various application areas of value assessment are presented and their requirements are discussed. A method for assessing the development of value during maintenance or renovation contract is presented.

This paper is a revised and expanded version of a paper entitled "Assessing the value of water supply networks" presented at Third International Engineering Systems Symposium (CESUN2012), Delft, Netherlands, 18-20.6.2012.

Keywords: Value assessment, water, sewer, pipelines, asset management, renovation, outsourcing

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1. Introduction

Water supply and sewerage services include the supply and distribution of water, and the collection and treatment of waste water. Water is generally extracted from surface or groundwater reserves. It is then purified and distributed to consumers in the public (or private) water supply. After the use, water is collected in sewerage systems, and then treated at waste water treatment plants before being released back into water courses. (Finland's Environmental Administration, 2009)

In Finland, like in most of the other European countries, the water supply and sewerage services (network maintenance and renovation) are provided mainly by public water utilities. The total length of water networks is about 100 000 km, as the length of sewer networks is roughly 50 000 km. The estimates of the economic value of the water and sewer systems range from about 10 to 20 billion € (ROTI, 2011; Piekkari, 2007). These systems were mainly built in the 1970s and 1980s, and the ageing systems require investments to maintain their value and reliability (e.g. Välisalo et al., 2007). The maintenance and renovation of water and sewerage systems has not been at a level required to stop the deterioration of the pipelines (e.g. Laitinen and Maasilta, 2011). The need of rehabilitation is recognized also in the international context (e.g. AWWA, 2001).

There are many reasons for the inadequacy of renovation and maintenance. A lack of resources (skilled employees, money, machinery etc.) in municipalities and the low prioritisation of renovation and maintenance activities are among the main obstacles the rehabilitation activities face. However, one of the most important reasons for the deficiencies in the rehabilitation of the water and sewerage systems is insufficient knowledge about the current condition of the pipeline assets (Laitinen and Maasilta, 2011) and thereby the value of the system.

An important application of the value assessment in the water sector is the assessment of the pipelines in order to follow up the development of the network's long-term value during a maintenance partnership contract. Perhaps the most important measure of the value in this case is the condition of the network. The deficiencies in assessing the value of the system are considered one of the main obstacles to the wider application of private-public and public-public (municipality-municipality) co-operation. Because of the unknown condition and structure of the pipelines, private companies are forced to add considerable risk premiums to their contract offers, which can be costly for the municipalities. On the other hand, the municipalities do not dare to make a maintenance partnership contract with e.g. a private company, because the network value and condition might deteriorate during the contract period due to lack of assessment methods.

The assessment of the value of the water supply system entails several challenges. In Finland, at least, there is no commonly accepted assessment method. The need for value assessment standards is also addressed in international context (Grigg, 2005). The assessment of value is more commonly practised in, for instance, the manufacturing industry and electricity distribution. Assessing the value of the water supply networks is challenged by the lack of usable, reliable and systematically gathered information about the condition of the networks and the various factors influencing the condition of the network.

The private and public sector are both in need of better criteria and tools for effective decision-making concerning maintenance and renovation. The value of the system should be addressed holistically: not only concentrating on the economic values and opportunities but also regarding, for instance, risks, social and environmental perspectives, quality of water and the technical and economic life of the network.

The main research question for this paper is as follows: “What are the requirements to a method to holistically assess the value of water and sewerage systems?” To answer this question, we discuss, comprehensively, the value assessment of water and sewerage systems and the applicability of various value assessment methods to the evaluation of the systems. The objective of this paper is to bring new perspectives to the assessment of value in the water sector and to create a method for assessing the value of networks. Technologies for assessing the value of pipelines are not focused on in this paper.

2. Research Methodology

This paper is based on literature research on, e.g., municipal reports and scientific publications as well as interviews with water supply network specialists in several companies and municipalities. The goal of the literature research is to find out the level of value assessment in the water sector, other related fields and research areas, and as a preparation for the interviews.

Semi-structured interviews were used to find out the level of condition and value assessment in Finnish water works and service providers. Altogether 15 different water works and service providers were interviewed in this phase. Informal interviews were used to learn more about specific techniques, tools and sources of information related to the value assessment, and to validate the outcome of the research.

From the scientific perspective, this study is conducted using qualitative research methodology as empirical data is collected from the researched phenomenon using in-depth interviews and observation as tools. Qualitative research methodology is selected because the goal of the research is to achieve a holistic perspective on the research object.

This study could be classified as a type of applied studies, which goal is to get new knowledge by producing normative applications, and more precisely as a study using constructive research approach. The constructive approach means solving problems through constructing models, diagrams, plans and organisations. (Kasanen et al., 1993)

The phases of constructive approach are:

1. Finding a practically relevant problem which has also research potential
2. Obtaining a general and comprehensive understanding of topic in question
3. Constructing a solution idea
4. Demonstrating that the solution works
5. Showing the theoretical connections and the research contribution of the solution concept
6. Examining the applicability of the solution. (Kasanen et al. 1993)

The final stage of the constructive approach ”examining the applicability of the solution” is not presented in this paper as the model (or construct) is not yet tested in practice full-scale.

3. Value Assessment as Part of Asset Management

Asset management can be defined as “the optimal life cycle management of physical assets to sustainably achieve the stated business objectives” (EFNMS, 2009). The management of network assets includes, for example, investment planning during the service life of the network, assessment of the network’s condition, determining the technical and service life, defining maintenance strategies, and planning and developing the operation and maintenance of the networks (Komonen et al., 2005). Evaluation and renewal of assets is one of the main components of asset management (Queensland Government, 2001). Thereby, value assessment is an important part of successful asset management.

In most of the value assessment methods, the value is addressed from various perspectives (e.g. Sánchez-Fernández et al., 2009). In general, the elements of value can be divided into monetary and non-monetary approaches. Elements of value may also be separated into shareholder, customer and stakeholder value (Reichheld, 1994).

The importance of assessing the economic value is stated in the asset management literature (Amadi-Echundu et al., 2007). However, in asset management, a holistic perspective is needed as the challenges have to be addressed from, at least, the business, information technological and engineering perspectives (Amadi-Echundu, 2006).

When contemplating asset management, the value can be measured using two basic types: capability and economic value. The capability value is measured on a physical scale whereas the economic value uses a monetary scale. Measures for capability value could be, for instance, processed units per second, length or weight. The economic value may also be presented in various forms, depending on the purpose of the asset. When the aim of the valuation is to identify how the money has been spent, the use of the original cost of the asset is appropriate. If the decision is about whether to retain or replace the asset, the present value of future cash flow (DCF) and the expected value from the disposal of the asset are relevant (Amadi-Echundu et al., 2007).

3.1 Value Assessment in Other Sectors

There are several examples of value assessment in other sectors, including real estate, electrical and other infrastructure, and business to name a few. The methods and their applicability to the water sector are evaluated in the following chapters.

In the real estate sector, the replacement value of buildings is very important when determining the real estate tax. The condition, quality and age of the building and the standard of equipment are also addressed when calculating the replacement value. In determining the replacement value, the selling price or actual costs of construction are not addressed (Finnish Tax Administration, 2010).

In the electrical network business, the replacement value is also in use. However, more advanced value assessment methods such as technical net present value (TNPV) are also used. When calculating the TNPV, the asset management value equivalent to the ratio of average life and technical and economic life is subtracted from the replacement value (Energy Market Authority, 2010).

Epstein (2008) argues that in assessing the value of business opportunities, environmental and social perspectives should be included as well as the economic perspective. Activity-based costing (ABC), life cycle costing (LCC) and full cost accounting (FCA) are mentioned as methods that can be used to take the direct and indirect impacts on sustainability into account. However, the valuation of the social and environmental perspectives is challenging (Holliday et al., 2002). Nevertheless, including the environmental and social impacts helps the companies to include the external costs in their value assessments and thereby gain an understanding of the costs committed to the companies’ processes, systems and activities (Epstein, 2008).

Benefits/costs ratio models are value assessment methods used in, for instance, determining the product and service value or customer-perceived value (Khalifa, 2004; Grönroos, 2000). The value of a product or service is the ratio of the perceived tangible and intangible benefits and costs (Huber et al., 2001; Day, 1990). Benefits/costs ratio models take the value elements that affect the whole life cycle of the product or service into account but fail to pay attention to the changes in the business environment (Khalifa, 2004).

Methods based on the balanced scorecard (Kaplan and Norton, 1992) have received some support among the valuation methods. For example, Barber (2008) adapted the balanced scorecard in assessing the value of supply chains. The main advantage of the scorecard models is the consideration of intangible factors, in addition to the tangible and monetary factors.

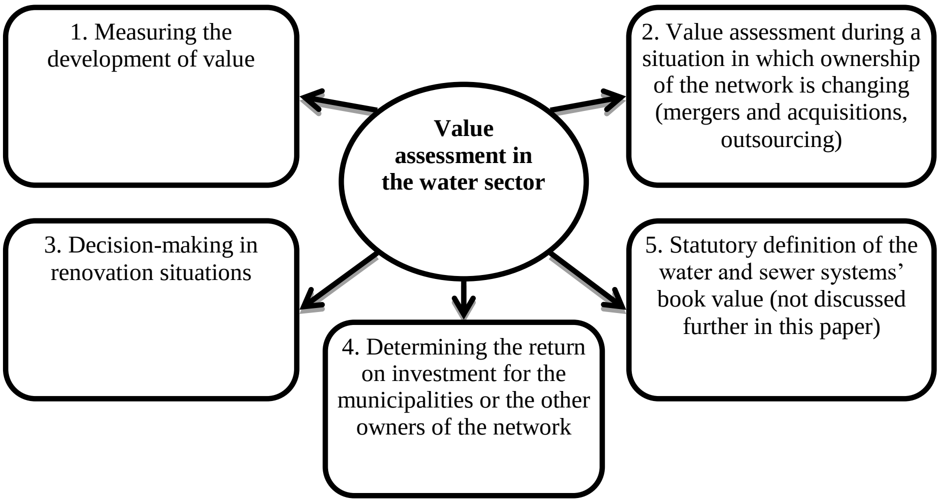
When addressing public organisations, public value is an interesting concept. Public value can be defined as "the value created by government through services, laws regulation and other actions" (Kelly et al., 2002). The public value paradigm states that the managers in public organisations have multiple goals that are broadly concerned with aspects such as steering networks of providers in order to create public value, create and maintain trust, and respond to the collective preferences of the citizenry in addition to those of customers (O'Flynn, 2007).

The holistic measurement of all the affecting factors, such as the intangible factors and public value, is challenging. However, the water sector could benefit from absorbing methods from other industrial sectors and scientific fields.

3.2 Why Assess the Value of Pipelines?

The application areas for the value assessment from the perspective of water and sewer systems are presented in Figure. 1.

Figure. 1. Application areas of value assessment in the water sector



In the first two cases, it is important to make the decision on whether to discuss the advantages and disadvantages in monetary terms or to use a more holistic approach, for instance, through technical and sustainability perspectives. Possible economic approaches include, e.g., the current replacement costs (CRC) and the net present value (NPV).

The information on the development of value can be used to monitor the effectiveness of renovation and rehabilitation activities. Important factors influencing the effectiveness of renovation include changes in the technical and economic life, the percentage of non-revenue water and number of pipe breakages, as well as the changes in other costs and in the quality of water.

To provide water services to the community, some water utilities have started to utilise external services – public or private – for renovation and maintenance. When outsourcing maintenance services, it is essential for the owner of the networks, i.e., municipalities, to know the condition and economic value of the property. Understanding the asset value is important, as a considerable amount of capital is invested in water and sewer systems, and their role to the community is crucial.

Value assessment of the pipelines provides useful information for the municipalities concerning the decisions on how and whether to renovate. The condition and value assessment yield information on which renovation methods and materials to use and also on the timing of the renovation. The decision-making, considering the prioritisation of renovation projects, has been addressed in the literature and some prioritisation methods already exist (e.g. Grigg, 2005).

In Finland, the Water Services Act (2011/119) states that the charges for water services may include only a minimum return on the capital and must be reasonable and equitable for all users. The charges must, however, be sufficient to cover the investments of the water works in the long term. The assessment of reasonable charges has been problematic because of the different accounting and renovation practices in the water works (Kuivamäki and Kolehmainen, 2011).

In this paper, emphasis is on decision-making in renovation situations and measuring the development of value. For decision-making in renovation situations, two practical examples are presented in chapter 4. In chapter 5, a method for measuring the development of value during maintenance or renovation contract is presented.

3.3 Value Assessment in the Water Sector

The main asset value of water and sewer systems is bound to the water and sewer pipes and the rainwater drains on which our paper focuses. The main indicator of the value of the system is thereby the condition of the pipeline. The system also includes pumping stations, water tanks, treatment plants, water collection points and water purification plants.

When assessing the value of the pipelines, the condition of the pipeline is an important factor. The criteria affecting the condition include, for instance, the technical and economic life of the pipe, pipe material, internal and external load, conditions preceding the use, pressure and failure mechanisms (Kekki et al., 2008; Grigg, 2005). Some of the factors affecting condition and durability of water supply and sewer systems are presented in Table 1.

Table 1. Factors affecting condition and durability of water supply and sewer systems.

Factors affecting the condition of pipelines	Water supply	Sewer
Internal load: Water quality	- Load caused by water quality - Corrosion caused by falling pH, alkalinity and hardness of water and increase in the amount of chlorides, sulphates and free carbon dioxide	- Sand and other particles in sewage wear the pipe out mechanically - Gases developed in sewage, too high or too low pH of sewage and solvents affect the durability of the pipe.
Internal load: Temperature of water	- The changes in the capacity of materials caused by changing temperatures	
	- The rapid changes in temperature of domestic water extracted from surface water reserves	- Increase in temperature increases the incidence of chemical and microbiological phenomena and affects the aggressiveness of sewage
Internal load: Microbiological phenomena	- Growth of microbes is affected by the nutrients in water such as phosphorus. Also the characteristics of pipe materials have an effect on the microbes	

Internal load: Mechanical load	- Pressure caused by water, changes in flow and pressure of water - Pressure caused by sewage and changes in flow - Hydraulic circumstances affect the materials through wear and hydraulic impacts
External load: Microbiological phenomena	- Microbiological corrosion in surfaces of pipelines caused by chemical characteristics (and aggressiveness) of soil
External load: External mechanical load	- Bending, bearing and tensile stress, and volume changes in material caused by changing temperature. Causes of external load are, for instance, frost heaving, traffic and earth-moving work.
Manufacturing and logistics	- Protection from ultra-violet radiation - Careless handling of pipe such as dropping and bending the pipe
Quality of installation and implementation	- Removing rocks in the excavation while installing the pipe etc.
Quality of work	- Lack of quality of work may considerably shorten the life cycle of the pipe, but does not usually become evident in implementation testing
Durability of pipe materials and instruments	- Quality of protection, joints and gaskets increases the durability of pipeline

The table above is meant for giving an overview of the factors affecting the condition of the pipelines. When making decisions on renovation or maintenance of pipelines, the factors presented above should be taken into account in addition to just the pipe material and installation year.

There are many challenges in assessing the value of water and sewer systems. The use of existing methods and tools is important in order to assess the value of the networks cost-effectively. The gathering of information is made more challenging by the fact that the pipelines are often difficult to reach. The pipelines are buried underground, which makes the evaluation of their condition difficult, although there are some technologies to monitor and evaluate the condition of networks (videotaping and sensor technologies etc.). In many cases, however, the only way to properly assess the condition of the outer surface is to unearth the pipe. In order to find out what is inside, the pipe must be cut open or the inner surface of the pipeline must be checked by using a special pipeline camera technology. The use of these methods is not economically viable on a large scale, which means that the municipalities require different methodologies to assess the value of the pipelines.

The location of the system (city vs. rural area) and the connected infrastructures (roads, other infrastructure) also affect the valuation of the system. The data, which act as a basis for the value assessment, are deficient, unreliable, unsystematically gathered and often scattered over many systems, ultimately making the value assessment only a rough estimate. The pipeline information is especially limited in some of the small municipalities and water works. The assessment may be based solely on information from old maps on the material and age of the pipeline and/or the experience and memory of the employees.

The difficulty of measuring all the factors affecting the condition and value of pipelines has encouraged water utilities to find out indirect measures of pipeline condition. These key figures help water utilities to cost-effectively indicate the condition and value of the pipelines. The conventionally used indicators are presented in Table 2.

Table 2. Key figures for the indication of pipeline condition.

Key figures	Description	Challenges of measurement
Non-revenue water	the amount of water that cannot be invoiced to the customers	length of network, pipe size and changes in water consumption not taken into consideration
Leakages and blockages	amount of leakages of water or blockages in the sewer system	damage and expenses caused by leakages vary considerably; the number of detected leakages depends on the time spent and the technique used; the weather conditions and the traffic load affect the number of leakages
Pipe breaks and interruptions	the number of unexpected leakages that needs repairing and interruptions to water distribution	significant changes in statistical and detective methods and no standard procedures to record the collected data, a varying operational environment, difficulty comparing the number of pipe breaks and interruptions between utilities and the distinction between pipe breaks due to actual deterioration and pipe breaks attributed to extraordinary environmental load

Non-revenue water addresses the amount of water pumped into the network that will leak out to the ground and cannot be invoiced to the customers. This includes water used by authorities, water theft and metering inaccuracies in addition to the leakages (International Water Association, 2012). In sewer systems, the non-revenue water invades the pipeline from the soil and causes additional expenses by straining the waste water treatment plants. A high leakage rate usually indicates poor network condition but on its own is not sufficient to explain the condition of the network because, e.g., the rainfall has a large effect on the sewer system leakage rate. The length of the network, the pipe size and the changes in water consumption are not taken into consideration, which reduces the reliability of the figure (Finnish Water Utilities Association, 2011, 25).

The key figure presenting the number of leakages or blockages describes how many leakages of water or blockages in the sewer system emerge per kilometre in one year. The number of leakages and blockages, however, is not enough to evaluate the actual condition of the network. The damage and expenses caused by the leakages vary considerably depending on, e.g., the size of the leakages. The number of detected leakages depends on, for instance, the time spent and technique used. Other external factors like weather conditions and traffic load also affect the number of leakages.

The condition of the water supply networks can also be assessed using the number of pipe breaks and interruptions in water distributions as indicators. A pipe break is an unexpected leakage that needs instant repair (Finnish Water Utilities Association, 2011, 29). An increased number of pipe breaks usually indicates poor condition of the network. Similarly, the interruptions caused by pipe breaks can be seen as a reflection of the network's condition. The number and duration of interruptions describe the preparedness of the water utility (or a leakage reparation service provider) to act in a crisis.

This figure also has disadvantages. Firstly, statistical and detective methods have changed significantly over time (Pöyry, 2011, 21) and utilities do not have standard procedures to record the collected data (Grigg, 2005). Secondly, the operational environment of the network (topography, population, etc.) varies, which makes the comparison of the number of pipe breaks and interruptions between utilities difficult. Thirdly, the distinction between pipe breaks due to actual deterioration and pipe breaks attributed to extraordinary environmental load, accidents, joint leaks, etc. is difficult or even impossible to make (Sægrov et al., 1999).

As discussed in this chapter, the conventional key figures and other methods for indication the value and condition of pipelines entail several challenges. This is also discussed by van der Hoop (2010), which claims that the conventional methods for assessing the water and sewer systems produce mainly rough estimates of value because of the many factors influencing the condition of the pipelines.

Thereby, when assessing the value of water and sewer systems and later using the same information as a basis for decision-making, it is crucial to increase the amount and quality of pipeline information. Furthermore, it is important to build a holistic method for assessing the value of the pipelines.

4. Practical Methods for Decision-making in Renovation Situations

For the assessment of the prioritisation of pipeline renovations, AWWARF (2001) presents three methodologies: voting for the simple cases, a spreadsheet with weighted evaluation criteria, performance measures and project ranking for the more complex cases, and multicriteria decision analysis for cases with multiple stakeholders with conflicting interests. Possible criteria for the prioritisation include a return on investment, risk allocation, and public sector and social issues (AWWSC, 2002; AWWARF, 2001).

As in the case of value assessment, the assessment of renovation related decisions should also be holistic. Some of the following criteria may be included in the assessment (Grigg, 2005):

- technological and managerial
- legal and institutional
- political and social
- financial and economic
- environmental

Technological and managerial criteria include, for instance, meeting the goals effectively, improving the service and reducing risk and vulnerability. Legal and institutional criteria may include legal feasibility and compliance with regulations, whereas political and social criteria may consist of negative impacts on people, integration to existing plans, political feasibility and impacts on public health.

Financial and economic criteria may include acceptability of return rate, reduced operating costs, and benefits and costs to the local economy. Lastly, environmental criteria could include positive or negative impacts on the environment.

Municipalities are in need of better decision-support methods to allocate their resources to the most effective renovation projects. For this purpose, two practical value assessment cases for the decision-making in renovation situations are presented. The first one addresses the value assessment of the water supply networks in the city of Turku, Finland, using current replacement costs (CRC) (Turun vesiliikelaitos 2011). Detailed descriptions of the second case can be found in Heinonen (2009).

The information needed to assess the CRC is the replacement price, pipe materials, size, building year and technical-economic life of the network. If some parts of the network had been renovated, the construction year (age) was the year of renovation. If the material of the pipeline was unknown, the pipe was considered to be plastic.

The CRC calculations were simplified by assuming that all pipelines (sewers, water pipes and storm water strains) were situated in the same ditch, which lowered the estimated unit prices. At the same time, the construction costs vary depending on whether the pipes are installed inside or outside the city plan area. If both of these factors are excluded from the calculations, they may compensate each other in a way that means that the final results are rather realistic. In the case of Turku, the location in terms of the city plan was addressed by giving these two groups different multipliers regarding the unit prices.

The CRC calculations give an overview of the value of water supply and sewer networks and they provide help in decisions regarding renovation budget and whether or not to renovate. However, the CRC does not take into account all the factors affecting the condition and value of the networks.

The second case contemplates a sparsely populated area in Finland. As the determined service life has an enormous impact on the results of the renovation need, the unit prices have a pivotal role when calculating the value of or the renovation debt in the network.

When assessing the renovation need, the service life has an essential role. Renovation need refers to pipelines and sewers that have reached the end of their service life. For instance, in this area, the definition of the theoretical renovation debt proceeds as follows: the information and calculations are based on the building year and a service life of 40 years. Practically, this means that as the first concrete sewers were installed in 1952, the renovation debt, i.e., the monetary value of renovation need, has built up from the year 1992 (40 years later) (Heinonen, 2009).

The renovation debt was approx. 15 112 metres in 2007. Using the unit price of 250 €/pipe metre, the estimated renovation debt in 2007 was 3 778 000 €. In practice, the service life of pipelines is dependent on many different factors, which are mentioned earlier in this paper. Using a lifetime of 30 years, the renovation debt would have been 8 649 500 €. However, when selecting a lifetime of 60 years, there is no debt and it starts to accumulate after year 2013.

Renovation debt calculations combine basic information, such as installation age and pipe material, into experience and knowledge in water utilities. It is highly dependent on the accuracy of pipeline information and the chosen unit costs which, in reality, vary considerably.

Both of the presented cases address the value assessment mainly in monetary terms. In the latter example, the service life (consisting of many intangible factors) was also considered. However, improved methodology is needed in the value assessment of the pipelines in renovation situations.

5. Practical Method for Measuring the Development of Value

The change of value caused by maintenance and renovation services is crucial information for both the municipalities and service providers. Municipalities need reasons for investing in the pipelines and service providers need to show the benefits of their services to the municipalities.

Water works measure the effectiveness of the services by following up the documentation of the service providers, in co-operation with quality control and health care authorities, and through own inspections. Videotaping of the sewer network is a common means of quality control in larger contracts and among more substantial water works. Some of the water works use simple figures, such as water loss-% per pipe kilometre or availability of clean water. Service providers find that the figures should be simple and should not cause considerable extra work to produce. As presented in earlier chapters, these methods and variables might not be sufficient to measure the development of value and condition of pipelines during maintenance and renovation contracts.

In order to reliably measure the value of maintenance or renovation service, several variables are needed as the basis of measurement. Existing multivariable methods, such as AHP (Saaty, 1980) or Utility Value Analysis (e.g. Götze et al., 2008) could be applied when necessary. The process of value assessment should be started by defining the needs of the stakeholders, such as water works, municipalities, citizens and service providers. Based on the needs of the stakeholders, variables indicating the value of the system are created. Third important step in the process is to define the sources of information and the methods used in the gathering of information. The requirements are presented in Table 3.

Table 3. Requirements for developing a method for measuring the development of value in water systems

Needs of the stakeholders	Variables indicating the value of the system	Sources of information
Condition of the network	Installation or renovation year, pipe material and type, structure of the system • amount of valves (large amount might indicate a poor quality of design) • installation technique • corners of a pipe and other spots that are challenging to renovate Video material (rarely used in clean water networks) Test results	History and maintenance data, maps, maintenance reports, videotaping, sensors and tests (loggers, tracer gas, flow measurement, pressure gauges etc.), unearthing the pipe, cutting the pipe open, experience, expert assessment
Reliability of the network	water loss per inner area of the	History and maintenance data,

(water loss, pipe breakages and interruptions, leaks and blockages, reduced maintenance/ repair activities)	pipe times total length of the pipe, number of breakages, blockages, interruptions, leaks and blockages and resulted costs in a year, Unavailability-% in a year	maps, tests (loggers etc.)
Water quality	Sense perception, changes in quantities of certain substances (pH, sulphate, chloride etc.)	Automatic and manual measurement
Increase in the value of production	Water loss per inner area of the pipe times total length of the pipe, Invoiced water	History and maintenance data, cost and profit information from information systems
Decrease in the maintenance and repair costs	Changes in cost of maintenance and repair activities, amounts of maintenance and repair activities performed compared to the long-term average	Maintenance reports, history and maintenance data
Reducing the risk and costs of environmental and safety hazards	Changes in perceived and actualised environmental and safety risks	Environmental and safety reports, maintenance reports, authorities
Increasing security of the network	Changes in perceived and actualised security risks	Security reports, expert assessment

Condition of the network can be measured in some cases (e.g. concrete sewers) by the installation year, but in some cases (e.g. clean water pipes made of plastic) require at least a visual assessment of the pipe. Reliability of the network can be measured, for instance, by the number of pipe breakages, blockages or leaks or the water loss-% in a year. History and maintenance data and tests that reveal the leaks are important sources of information in this category.

Water quality is usually measured by tasting the water and measuring changes in levels of certain substances in water. Increase in value of production is a result of increased invoiced water from the customers and the data is usually accessible in information systems of water works.

Decrease in the maintenance and repair costs can be measured by assessing changes in maintenance and repair activities compared to the long term maintenance and repair activities. Reducing the risk and costs of environmental and safety hazards could be measured by changes in perceived and actualised risks. Sources of information can be environmental and safety reports and authorities. Security of the network could be a concern for the stakeholders, which can be measured by changes in perceived and actualised security risks. Information on security risks can be found on security reports or expert assessments which both are nowadays rarely executed among water works and service providers.

To fulfil the needs of water works and service providers regarding the assessment of the development of value, a simple checklist could be sufficient. A separate checklist should be made for clean water and sewage systems, where the quality criteria and the required quality levels would be present. An illustration of the checklist is presented in Table 4.

Table 4. An illustration of a checklist for a clean water system.

Figure	Level before renovation or maintenance	Level after renovation or maintenance	Level X years after renovation or maintenance
Water loss-%	2	4	4
Unavailability-%	3	3	4
Water quality	2	4	4
Maintenance and repair costs	2	3	3
Invoiced water	1	2	2
Flow measurement for condition assessment	2	3	2
Environmental and safety and security risks and costs	3	3	3

In this illustration, seven figures were chosen to represent the value of the clean water network. The levels of the figures are presented on a scale from 0 to 5, 5 being the highest level. Most of the figures are unique to the water works and service providers and the comparisons between them may be challenging. For instance, if a water work serves a large area with relatively small amount of customers, the water loss-% is usually worse than that for a densely populated area. The figures are only indicative and will become more accurate with practical testing.

Attention should be paid to weighting of the factors and variables, so that the measurement would highlight the most important value elements. Weighting should most likely be made case-specifically and also external experts could be used. Certain minimum and maximum thresholds could be set for the measures. Crossing the threshold should cause an action from the liable stakeholder.

Choosing the reference period is a central decision in value assessment. Value should be measured before the service contract and years after the service contract to find out the effects of the renovation or maintenance activities. However, also external factors, such as accidents and weather conditions, may cause negative development in the value of the pipelines.

The goal of the checklist is to emphasise the holistic nature of the value assessment regarding water and sewer systems. It is a step towards reliably measuring the effectiveness of maintenance and renovation activities. Implementing more holistic value assessment method may improve trust between service providers and municipalities, and thereby enable wider application of public-private co-operation.

6. Conclusions

There is no conventionally accepted method for assessing water supply and sewer systems. The information on changes in the value of network assets would be especially important during maintenance partnerships, such as public-private partnerships. With this information, the private and public partners could evaluate the success of their partnership objectively and holistically. In public-private partnerships, the absolute value of the network is not as important as the value at the end of the maintenance or renovation contract in relation to the starting phase of the contract.

The research question of this paper was: “What are the requirements to a method to holistically assess the value of water and sewerage systems?” In this paper, the focus was on the value assessment in the water sector, especially on renovation related decision-making and measuring the development of value. When assessing the condition of water and sewer networks, reliable, usable and systematically gathered information is required. Information about the condition of the network should be combined with theoretical models and use experiences. Currently, in order to directly assess the condition of sewer network, it must be cut open or use particular pipeline camera technology. Regarding clean water networks only indirect indicators can be economically used. Indirect indicators about the condition of the system include, for instance, renovation and maintenance reports, measurements using sensor technologies and historical information on leakages, blockages, non-revenue water, pipe breaks and interruptions.

The value assessment methods in the water sector need to consider the various value elements. Value elements include tangible and intangible elements, such as economic value, capability value, network condition and its many affecting factors, sustainability-related values and public value. The intangible values should be better represented in the decision-making process, which nowadays concentrates on the economic costs and outputs. A multi-criteria decision-making model (as suggested by Grigg (2005)) tailored to the needs of water works and private companies is needed.

A holistic approach to the value assessment is needed, but because of the limited resources of the municipalities, the approach should be executable with the current equipment. A value assessment method that could be implemented in practice in municipalities and private companies would be especially important.

In this paper, two practical cases of renovation related decision-making were presented. Based on these cases, decisions on renovation projects would benefit from more comprehensive value assessment methods. As highlighted before, more water and sewer network related information should be collected and analysed to make more risk-conscious decisions on whether, how and/or when to renovate.

In this paper, we presented the key figures that should be measured and combined them into a method that can measure the development of value during maintenance or renovation contract, but additional work is needed to create a standardised value measurement method. Practical testing is still needed to adjust the method to the needs of the case company and later on generalise the method.

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References

AWWA (2001) *Dawn of the Replacement Era: Reinvesting in Drinking Water Infrastructure*. American Water Works Association.

AWWARF (2001) *Financial and Economic Optimization of Water Main Replacement Programs*. American Water Works Association Research Foundation, Denver.

AWWSC (2002) *Deteriorating Buried Infrastructure Management Challenges and Strategies*. White Paper. http://www.epa.gov/ogwdw/disinfection/tcr/pdfs/whitepaper_tcr_infrastructure.pdf (Accessed 27.1.2012).

Barber, E. (2008) 'How to measure the "value" in value chains,' *International Journal of Physical Distribution & Logistics Management*, Vol. 38, No. 9, pp. 685-698.

Day, G. (1990) *Market-Driven Strategy: Processes for Creating Value*, The Free Press, New York, USA.

Energy Market Authority (2010) *Selvitys sähköverkkotoimintaan sitoutuneen pääoman määrittämisestä*. Report 52K30042.11-Q070-001. http://www.emvi.fi/files/Raportti_Poyry_2010.pdf. (Accessed 30.1.2012). In Finnish.

Epstein, M. (2008) *Making Sustainability Work: Best Practices in Managing and Measuring Corporate Social, Environmental, and Economic Impacts*, Greenleaf, Sheffield, UK.

EFNMS (2009) *A Definition of Asset Management*. Minutes of Meeting. European Federation of National Maintenance Societies. Trondheim, Norway.

Finland's Environmental Administration (2009) *Water services*. http://www.ymparisto.fi/default.asp?node=7368&lan=en (Accessed 3.12.2012).

Finnish Tax Administration (2010) *Kiinteistön verotusarvo kiinteistöverotuksessa* [the value of real estate in real estate taxation]. http://arkisto.vero.fi/print.asp?article=896&language=FIN&domain=VERO_MAIN&path=5,40 (Accessed 30.1.2012). In Finnish.

Finnish Water Utilities Association (2011) *Vesihuoltolaitosten tunnuslukujärjestelmän raportti* [Report on key figure system of water works]. Vesi- ja viemärilaitosyhdistyksen monistesarja, 29. Helsinki, Finland. In Finnish.

Grigg, N. (2005) 'Assessment and renewal of water distribution systems,' *Journal of American Water Works Association*, Vol. 97, No. 2, pp. 58-68.

Götze, U. et al. (2007) *Investment Appraisal*, Springer, Berlin, Heidelberg.

Grönroos, C. (2000) *Service Management and Marketing: A Customer Relationship Management Approach*, John Wiley, Chichester, UK.

Heinonen, J. (2009) *Evaluation of negative balance of renovation action in water and sewer systems in Akaa*. Thesis, HAMK University of Applied Sciences. https://publications.theseus.fi/bitstream/handle/10024/5260/Heinonen_Jukka_1.pdf?sequence=2 (Accessed 30.1.2012). In Finnish.

Holliday, C. et al. (2002) *Walking the Talk: The Business Case for Sustainable Development*, Greenleaf, Sheffield, UK.

Huber, F. et al. (2001) 'Gaining competitive advantage through customer value oriented management,' *The Journal of Consumer Marketing*, Vol. 18, No. 1, pp. 41-53.

International Water Association (2012) *Non-Revenue Water*. http://www.iwahq.org/1ny/themes/managing-utilities/utility-efficiency/non-revenue-water.html (Accessed 12.12.2012).

Kaplan, R.S and Norton, D.P. (1992) 'The balanced scorecard: Measures that drive performance,' *Harvard Business Review*, Vol. 70, No. 1, pp. 71-79.

Kasanen, E. et al. (1993) 'The constructive approach in management accounting research,' *Journal of Management Accounting Research*, Vol. 5, 243-264.

Kekki, T. et al. (2008) *Vesijohtomateriaalien vauriot ja käyttöikä Suomessa* [Damages and service life of water pipeline materials]. Vesi-instituutin julkaisuja 3. http://www.prizz.fi/linkkitiedosto.aspx?taso=2&id=547&sid=671 (Accessed 30.1.2012). In Finnish.

Kelly, G. et al. (2002) *Creating Public Value: An Analytical Framework for Public Service Reform*, Discussion paper, The Cabinet Office Strategy Unit, UK.

Khalifa, A.S. (2004) ‘Customer value: a review of recent literature and an integrative configuration,’ *Management Decision*, Vol. 42, No. 5/6, pp. 645-666.

Komonen, K. et al. (2005) *Käyttöomaisuuden hallinta – Asset Management*. VTT Research Report BTUO43-051362, VTT Technical Research Centre of Finland. In Finnish.

Kuivamäki, R and Kolehmainen, R. (2011) ’Kaksi ongelmaa, yksi ratkaisu? Vesihuoltoliiketoiminnan valvonnan tarve ja tavoitteet [Two problems, one solution? Need of control and objectives in water business],’ *Vesitalous*, No. 5, pp. 5-7. In Finnish.

Laitinen, J and Maasilta, M. (2011) ‘New Approach to Sewer Renovation Programmes’. Proceedings of the 12th Nordic/NORDIWA Wastewater Conference, FIWA, Helsinki Finland, pp. 162-171.

O’Flynn, J. (2007) ‘From New Public Management to Public Value: Paradigmatic Change and Managerial Implications,’ *The Australian Journal of Public Administration*, Vol. 66, No. 3, pp. 353-366.

Piekkari, J. (2007) ‘Verkostojen rappeutuminen uhkana vesihuollon toimintavarmuudelle [Degradation of networks as a threat to the reliability of water services],’ *Vesitalous*, No. 3, pp. 5-6. http://www.vesitalous.fi/upload/lehtiarkisto/2007/3-2007.pdf (Accessed 1.2.2012). In Finnish.

Pöyry (2011) *Verkostosaneerausten vaikuttavuuden arviointi* [Assessment on the effectiveness of network rehabilitation]. Loppuraportti 67090591.BBP.
http://www.vvy.fi/files/1441/Loppuraportti_11042011_verkostosaneerauksen_vaikutustenarviointi.pdf (last accessed 31.7.2012). In Finnish.

ROTI (2011) Rakennetun omaisuuden tila 2011 [The condition of built assets 2011]. www.roti.fi (Accessed 7.2.2012). In Finnish.

Saaty, T.L. (1980) *Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, New York: McGraw-Hill.

Sægrov, S. et al. (1999) ‘Rehabilitation of water networks – Survey of research needs and on-going efforts,’ *Urban Water* Vol. 1, pp. 15-22.

Turun vesiliikelaitos [Water services of city of Turku] (2011), *Vesihuoltolaitosten käyttöomaisuuden tekniset nykykäyttöarvot* [Current replacement costs of assets of Turku’s water works]. Turun Kaupunginhallituksen 10.10.2011 pöytäkirjan 026/2011 liite [Appendix 026/2011 of proceedings of Turku’s city government 10.10.2011].

Välisalo, T. et al. (2007) ‘Pipeline asset management by Finnish water and sewage works,’ Proceedings of the 10th Nordic/NORDIWA Wastewater Conference, NORVAR, Hamar, Norway, pp. 167-176.

Water services act (2001/119) *Chapter 4, Section 18*. http://www.finlex.fi/en/laki/kaannokset/2001/en20010119.pdf (Accessed 1.2.2012).

Publication V

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A method for visualisation of uncertainty and robustness in complex long-term decisions

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A method for visualisation of uncertainty and robustness in complex long-term decisions

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ABSTRACT: The long lifetimes of infrastructure have implications for investment decision-making and it is difficult for purely monetary indicators to capture all the relevant issues. Furthermore, uncertainties grow as the investment period grows. Long-term perspective calls for the use of scenarios, and usually requires the opinions of different stakeholders and experts. Furthermore, performance cannot always be modelled by formal methods, such as simulation. Because of the deep uncertainties involved, organizations' strategies should be robust, i.e. any strategy implementation should perform adequately irrespective of which scenario will materialize.

Strategy Robustness Visualisation Method is a method for taking the deep uncertainties related to long-term strategies and various stakeholder perspectives into account. The key feature is the modelling of uncertainty of the quantitative indicators by {min, max}-values plotted on radar plots such that each strategy option's performance, under each scenario, can be visually inspected for uncertainty and robustness.

1 INTRODUCTION

When discussing long-term strategies combined with deep uncertainty and complex decision environments, there is a need for strategies that are flexible and robust under several different scenarios. The benefits of robust solutions are highlighted especially for long-term investments (Berkhout et al, 2013).

According to Scrieciu et al. (2014), uncertainty may refer to (1) the lack of agreement among interested parties, (2) lack of analytical approaches to analyze the issue at hand, (3) lack of knowledge about the state and trends of the parameters affecting the issue at hand issue or (4) any combination of these. Deep uncertainty can be defined as a situation where decision makers do not know or cannot agree upon the full set of risks to a system or their associated probabilities (Lempert and Groves, 2010, Kasprzyk et al, 2013). For instance, land use change, the depletion of resources, and climate change can be counted as changes that introduce deep uncertainties. Under conditions of deep uncertainty calculations of expected value of the objectives and constraints may not suffice to characterize the state of knowledge. (Kasprzyk et al, 2013)

Adaptive management is an approach that can be used in conditions of deep uncertainty, as it recognizes that strategies and policies are based on current knowledge, predicted conditions, and objectives, but must be flexible for adaption to future conditions as these emerge, thereby promoting a continual learning process (Hamilton et al, 2013). The assumption underlying adaptive management is that the future will in part evolve in ways unanticipated by even the best scientific models. Therefore, a decision-maker does not develop a firm and unchanging strategy that will remain in place for decades, but rather uses the current scientific knowledge to develop strategies that will remain in place for a short time horizon, and then adjusts these strategies as future unfolds.. For adaptive management, flexibility and robustness in the face of changing circumstances are the key features of any strategy adopted.

Flexibility can be defined as "ability to change in response to altered circumstances" (Adger et al, 2005). It can be maintained by, for instance, linking solutions with other solutions in order to minimize implementation and transaction costs, finding solutions that can be justified for a broad range of scenarios, making solutions switchable, scalable, thus avoiding rigid one-time investments that produce ‘lock in’ or waiting for better information and assessments, or for opportunities not foreseen right now (Triantis, 2003).

2 MOTIVATION

It is important to note that in a multi-stakeholder decision context there is usually an agreement about the set of scenarios; which variables are included, which time frame is considered, and how many scenarios will be enough to represent the future pathways. There is, however, less agreement about the *performance levels and related value* of the optional strategies. It should be noted that a scenario provides conditions that are not controllable by the strategies available by the stakeholders in the decision context considered.

The approach presented in this paper aims at revealing robust strategies as defined above. The approach combines elements from two known methods: Multi-Criteria Decision Analysis (MCDA) and Robust Decision-Making (RDM). Linkages to these methods are presented in the Discussion section. The key feature of the approach is *visualization of strategies’ robustness*, which allows a partial adoption of the MCDA and RDM methods.

3 STRATEGY ROBUSTNESS VISUALISATION METHOD (SRVM)

SRVM consists of seven iterative phases as shown in Figure 1.

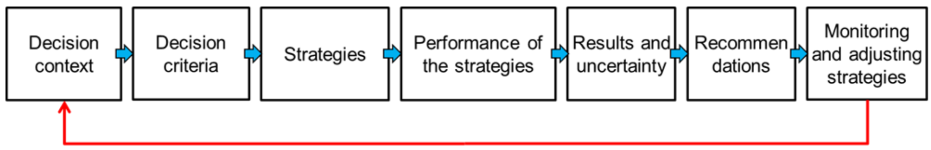

Figure 1. SRVM supports complex strategic decisions under deep uncertainty.

Hence, there is a need for revealing this particular uncertainty in order to identify is there a strategy that would indicate robustness under stakeholders’ beliefs about its performance.

In this paper we will adopt a relative measurement of performance: how an optional strategy will perform relative to the currently adopted. The following definition is introduced:

“A strategy is robust if its deviation from the current strategy is positively valued across the range of impact criteria under the given scenarios”. This definition is developed further from the definition presented by Lempert et al. (2006) which defines a robust strategy as a strategy that “performs relatively well – compared to alternatives – across a wide range of plausible futures”.

Decision context: During the first phase, the decision environment is defined, including identifying the stakeholders and all the important factors affecting the decisions, and selecting and involving the relevant stakeholders in the process. Additionally, the basic scenarios to test the performance of the strategies are selected or created.

The described scenarios are future conditions under which the strategies perform differently regarding several criteria that are considered important by stakeholders. An important aspect of the scenarios is that they have no probabilities attached to highlight the deep uncertainty regarding the future. They are treated instead as possible futures in which it is desirable for the strategies to perform well.

The stakeholders may select a role they represent (i.e. research or governmental decision-maker) which can be used in the analysis to separate the results into the categories of stakeholders.

Decision criteria: Next, the most important decision criteria for the strategies are selected. The only requirement for defining a criterion is that it contains no reference to time (calendar time), i.e. it is time-invariant. This makes possible strategy evaluation also across time periods. The selection process should be done in co-operation with the stakeholders. The scale of each criterion is assigned in co-operation with the stakeholders. The scale is, for instance, from -2 (maximum decrease in performance against that criterion) to +2 (maximum increase in performance against that criterion) compared to the baseline strategy business-as-usual. Thus, decision criteria evaluate the deviations of the performance of the decision criteria from the baseline scenario. For instance, -2 may mean a 50 percentage or more decrease in the performance compared to the baseline; +2 may mean a 50 percentage or more increase.

Strategies: After selecting the decision criteria, the most important strategies to be assessed within the decision context are selected. Stakeholders could also be involved in this phase, especially if the distribution of benefits/costs/risks between stakeholders is considered unbalanced. The number of decision criteria and strategies should be kept reasonable by, for instance, voting for the most important criteria and strategies and choosing them for further analysis.

Performance of the strategies: During this phase, each adaptation strategy is assessed against each decision criterion, under all specified scenarios in turn. For quantification of a strategy's performance, each decision criterion is associated with a performance metric called a Key Performance Indicator (KPI). The KPIs can be measured by ordinal or cardinal scales. The KPIs are defined such that a higher value is more preferred than a lower value. (NOTE! We assume that no strategy has the capability of changing the scenario to another scenario).

The measurement of strategy performance is conducted by two means: Stakeholders assign performance scores based on their understanding of how a strategy performs against a KPI under the specified scenarios.

If there are several expert opinions for a KPI, we expect to see a distribution of scores. Secondly, system modelling can be used to provide KPI values. The model results can be in the form of probability distribution functions (pdf's).

Thus we have distributions of scores/values with respect to the KPIs – in fact different distributions for each of the scenarios under which the KPIs are measured.

As a simplification, SRVM only uses two value-pairs from the score/value distributions, labelled 'optimistic' and 'pessimistic'. In the case we have a distribution of values, we associate the percentiles KPI0.05 and KPI0.95 with pessimistic and optimistic, respectively (see Figure 2). Similarly, the variation of expert opinions is reduced to pessimistic and optimistic values only by taking the minimum and maximum scores (see Figure 3). We adopt the following interpretation of the variation of experts' scores: Each expert has her/his view on the implementation of a strategy in terms of technology and running of the system, also taking into account the inherent flexibilities or real options associated with the operational solutions, thus leading to variations in the perceived performance of the strategy.

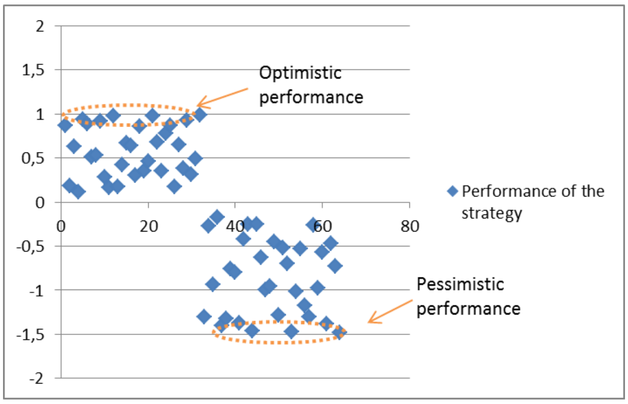

Figure 2. An example of selecting the optimistic and pessimistic modelling results for the analysis.

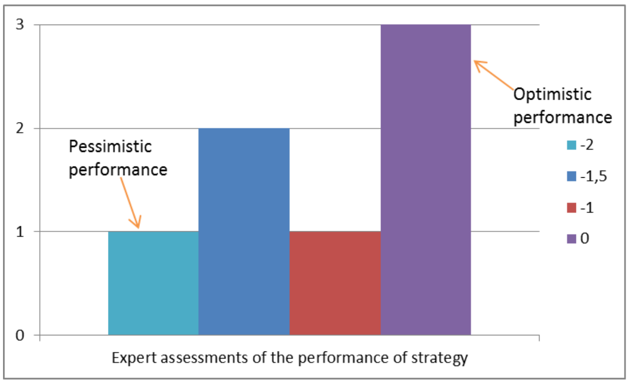

Figure 3. An example of selecting optimistic and pessimistic expert opinion based results for the analysis. Vertical axis represents the number of votes assigned and horizontal the different performance levels (-2, -1.5, -1, 0 in this case).

Group decision support systems (GDSS) can be used to support the first four phases of the method but especially this phase. One has to be careful in labelling the outcomes congruent with the direction of the scale.

Results and uncertainty: The visualization of the performance of strategies, with uncertainty ranges specified by the {min,max}-pairs of pessimistic and optimistic performance, is based on radar plots as shown in Figure 4, Figure 5 and Figure 6. The performance of a strategy is shown under all the scenario combinations in one plot.

The uncertainty is shown by plotting two similar-colour lines; one that links the pessimistic values, and the other linking the optimistic values of the KPIs under a given scenario. As uncertainty increases, the distance between these two lines increases. For each scenario such line pairs are plotted on the same radar plot, with different colour per scenario. Visually, robustness is shown by several line-pairs which are close to each other for all scenarios. Visual inspection of performance is found to be the most helpful way for supporting the choice of robust strategies (Montibeller and Franco, 2010). Especially, those strategies that are insensitive for both short- and long-term scenarios are so called ‘low-regret’ strategies.

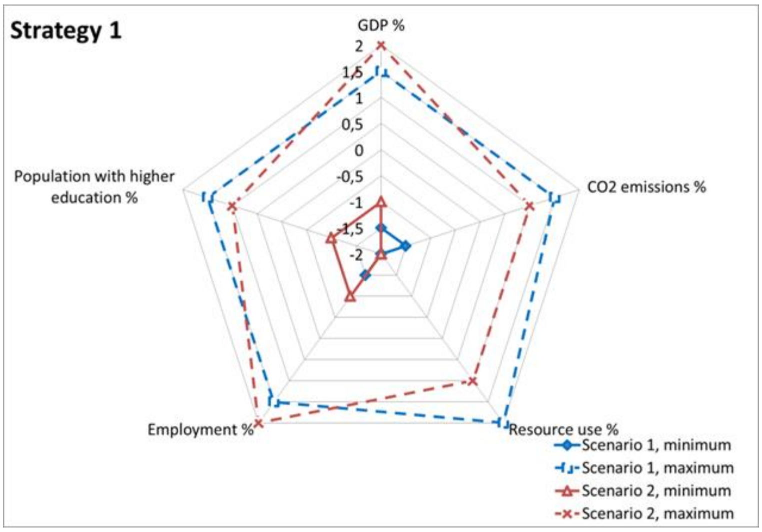

Figure 4. Performance of the Strategy 1. Uncertainty is depicted by {min,max}-pairs obtained from model computations and experts' opinions. There is a high variance in the optimistic and pessimistic performance, but the performance is fairly similar in both scenarios.

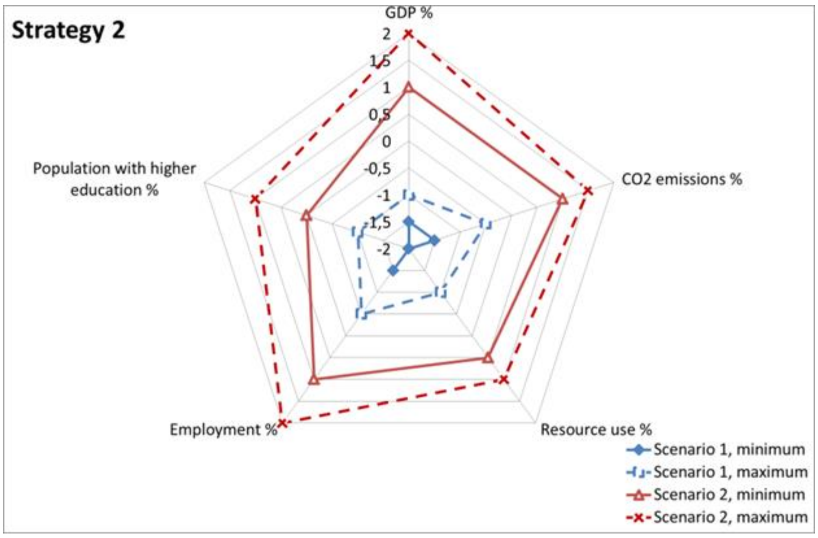

Figure 5. Performance of the Strategy 2. There is a high variance in the performance of the strategy in the scenarios 1 and 2, but the variance of the optimistic and pessimistic performance inside the scenarios is fairly low.

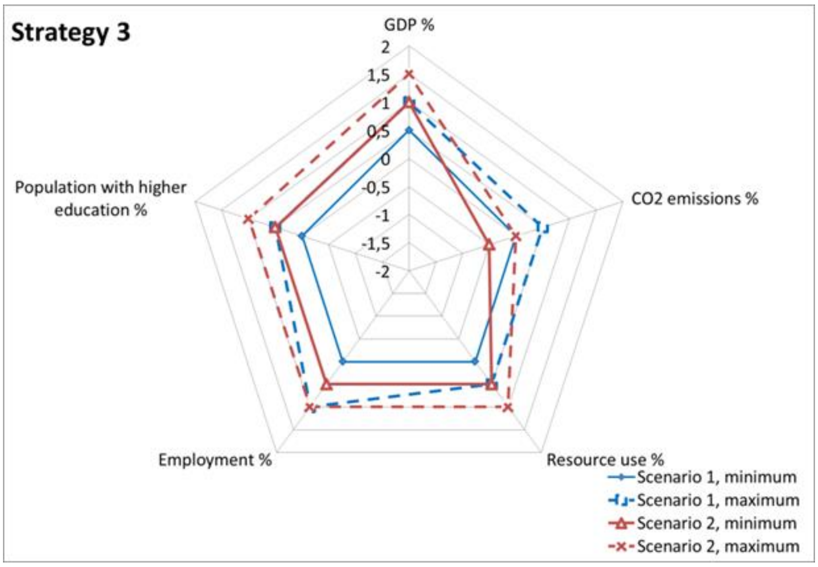

Figure 6. Performance of the Strategy 3. The variance between the scenarios and the optimistic and pessimistic performance values is low. In comparison to the Strategies 1 and 2, this is a robust strategy.

Furthermore, the plot can be used for ranking as well: the higher up on the arms the lines are clustered, the higher is the performance. It should be noted that one of the key decision criterion is usually the cost of implementing a strategy which typically shows bad performance of a strategy that otherwise performs well against the other criteria.

However, in some cases, the difference in performance of the decision criteria compared to the baseline is so extensive that the cost of implementing the strategy becomes meaningless. The cost of a strategy can also be explicitly taken into account, so that it can be, for instance, expensive but has the same cost in each scenario or cheap in one scenario and expensive in the other.

Recommendations: The recommendations to the decision-makers are related to the robustness, or non-robustness (vulnerability) of the strategies. Irrespective of identifying a robust strategy, the key uncertainties should be pointed out.

It is expected that expert opinions are very uncertain in situations where the assessment horizon is long, say 2070, and the performance is only partially controlled by any of the strategies. A remedy to deep uncertainty, as depicted by large visual deviations of performance between scenarios, is a re-specification of the decision context such that more strategy options enter the assessment adding also flexibility to the initial ones due to synergistic combinations. Such flexibility would show in model results and expert opinion as higher scores, especially the minimum value of the {min,max}-pair, as the hedging potential of the new strategies would be looked at in the search for robust strategies.

Monitoring and adjusting implemented strategies: As the decision context changes (partly due to the fact that scenarios get updated due to new information), implemented strategies need reviewing. The strategies should be reviewed especially for possible need to rescale, modify, or renew them.

4 DISCUSSION

Several complementary methods can be used in supporting strategic decision-making (e.g. Hinkel and Bisaro, 2014). Multi-Criteria Decision Analysis (MCDA) considers multiple objectives or criteria in decision-making environments. MCDA methods offer systematic frameworks that help synthesize both subjective and objective information (Salo and Hämäläinen, 2010). Especially in complex decision contexts, there are multiple and potentially conflicting decision criteria that need to be evaluated in decision-making. The performance of each decision option is measured using scales that are good proxies of the decision criteria. Cost performance is usually one of the main criteria, although potentially in conflict with other criteria the decision-maker(s) want to pursue. Cost stems from using resources which can be found at any level and sector of society; governance, business, households, individuals, etc. An important feature of MCDA is the evaluation of performance using scores which stakeholders and decision-makers assign to the performances of the options under the scenarios. These scores can vary, as well as the criteria weights, among the assessors. Linkov et al. (2006) present MCDA as one of the key methodologies to support adaptive management.

MCDA methods often treat uncertainties using probability distributions and/or sensitivity analyses. These approaches are adequate for situations when such probability distributions can be developed and the selection of optimal strategy is relatively insensitive to the key assumptions such as specification of model and distributions (Lempert et al, 2006). On the contrary, Robust Decision-Making (RDM) seeks strategies that are insensitive to the most significant uncertainties (Lempert et al, 2006). RDM essentially provides an analytical decision-support framework for situations characterized by high uncertainty. Rather than attempting to make decisions on the basis of any single prediction of future states in variables of interest, or any single probability density function characterizing uncertainty in outcomes, RDM attempts to identify the full range of plausible scenarios and, on that basis, make decisions that are robust across as wide a range as possible of those future states. However, a comprehensive set of scenarios, decision criteria and strategies cause difficulties for the analysis and visualization of results.

In this paper, we present the Strategy Robustness Visualisation Method (SRVM) which is a method for taking the deep uncertainties related to long-term strategies, complex phenomena and various stakeholder perspectives into account. Furthermore, the method should be easy to understand and visually intuitive. Therefore, we have adopted only partially features of the MCDA and RDM approaches. The SRVM is lighter analytically than the aforementioned methods, focusing on visualization of system performance and its uncertainties.

The concept of robustness is similar to the RDM method as described in Lempert et al. (2006). The problem with the RDM method relates to the visualization of performances of hundreds of scenarios when the number of criteria is larger than two. Similarly to RDM, SRVM does not assign probabilities to scenarios but describes the few scenarios in such detail that stakeholder experts are comfortable in giving an opinion about the performance of the strategies under each scenario.

The SRVM follows MCDA in terms of performance and preference modelling but limits measurement to single criteria without combining the criteria into a single value (or utility) measure by an additive value (or utility) function. Thus, the criteria are not weighted by the stakeholders.

Robustness is a key property of strategies, especially in case of long-term strategies such as those related to climate change adaptation. The SRVM method presented here has been guided by the need to visualize robustness in a multi-criteria assessment situation, especially in long-term decision-making where several futures can be envisaged. A robust strategy can be interpreted as a low-regret strategy that performs satisfactorily (Simon, 1956) in most future conditions. Performance cannot always be modelled by formal methods, such as simulation. Also the subjective opinions of experts are needed for comprehensive assessments.

The method enables a rough assessment of the robustness and vulnerabilities of the selected strategies. It uses only {min,max}-values if value distributions (pdf's or intervals) of the performances under the scenarios are available. The rationale in this selection is that all the expert opinions are of equal value and the different experiences of the experts should be respected. In case of a clear outlier, iterative rounds of analysis should be considered to ensure that no errors were made in the input of data. From the perspective of robustness, the optimistic and pessimistic values are of equal importance.

In order to visualize robustness of performance with respect to several criteria the radar plot technique was selected. As each scenario yields two performance curves (optimistic and pessimistic) the plot gets quickly 'messy' when the number of scenarios grows. It seems, based on the applications presented above that at least two scenarios can still be plotted such that robustness can still be identified from the spider plots which are simple to produce. The visualization of the robustness could be improved by checking it against the principles of Tufte (1983).

Even though the method does not use the average performance levels, they might still be useful complementary information for the decision-makers. In some cases, average performance levels can be used to guide a refinement of the assessment when large deviations from the average occur. The use of GDSS may be helpful during the development of the decision context, decision criteria, the alternative strategies and the performance of the strategies. However, attention should be paid to the facilitation of the expert sessions. Iterative rounds of assessment may be needed to ascertain that the decision context is understood.

The examples of radar plots in this paper represent ideal cases of robustness. In practical applications of SRVM, the radar plots require more analysis and interpretation to utilize the visualizations for decision support.

5 CONCLUSIONS

In this paper, we present a method for visualizing and assessing the uncertainties and robustness of alternative long-term strategies. The key feature of SRVM is the modelling of uncertainty of the quantitative indicators by {min, max}-values plotted on radar plots. In this approach, each strategy option's performance, under each scenario, can be visually inspected for uncertainty and robustness. SRVM is tested in two longitudinal case studies related to climate change adaptation in the energy sector, which will be published later. An example of the first case is presented in Figure 7 and Figure 8.

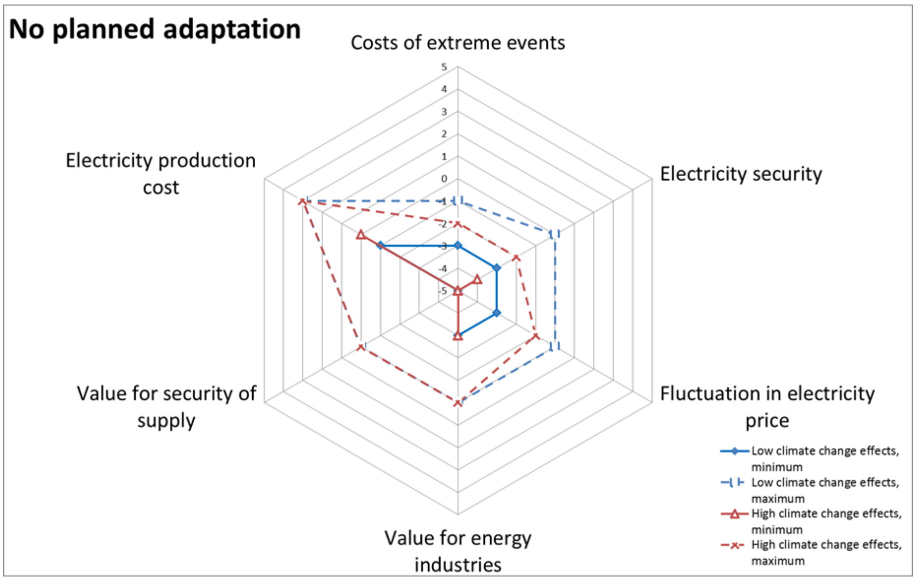

Figure 7. Visualisation of the adaptation strategy "No planned adaptation" (Hanski et al. 2015).

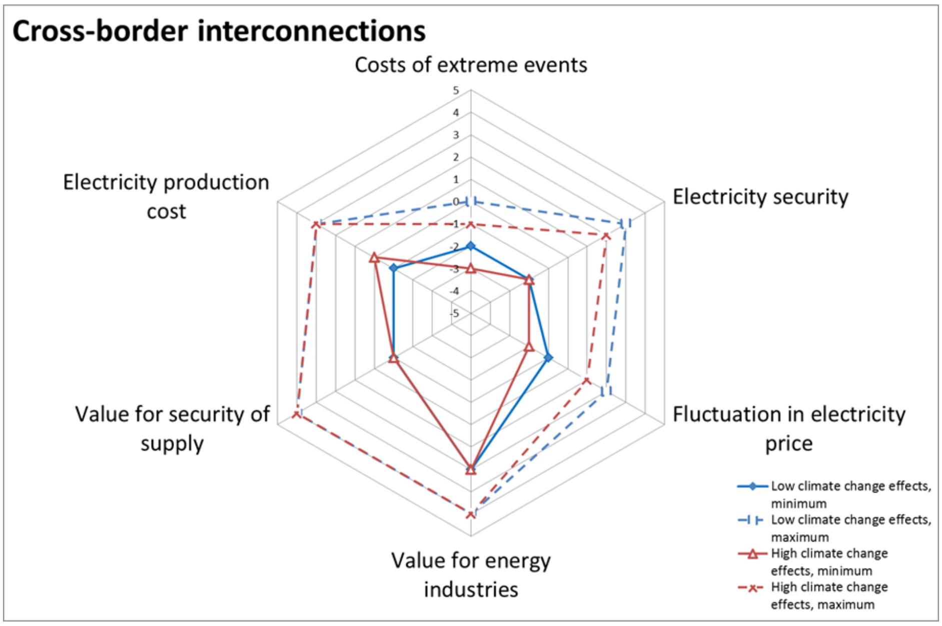

Figure 8. Visualisation of the adaptation strategy "Cross-border interconnections" (Hanski et al. 2015). Robustness or non-robustness is not as clearly visible as in the hypothetical examples.

ACKNOWLEDGEMENTS

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REFERENCES

Adger, N, Arnell, N. & Tompkins, E. 2005. Successful adaptation to climate change across scales. *Global Environmental Change*. 15(2): 77-86.

Berkhout, F., Bouwer, L., Bayer, J., Bouzid, M., Cabeza, M., Hanger, S., Hof, A., Hunter, P., Meller, L., Patt, A., Pfluger, B., Rayner, T., Reichardt, K. & van Teeffelen, A. 2013. *European responses to climate change: Deep emissions reductions and mainstreaming of mitigation and adaptation*. Key findings of the European Commission FP7 RESPONSES project. Policy Brief.

Hamilton, M.C., Thekdi, S.A., Jenicek, E.M., Harmon, R.S., Goodsite, M.E., Case, M.P., Karvetski, C.W. & Lambert, J.H. 2013. Case studies of scenario analysis for adaptive management of natural resource and infrastructure systems. *Environmental Systems & Decisions* 33: 89–103.

Hanski J, Rosqvist T, Crawford-Brown D (2015) ToPDAd deliverable D4.3 - Demonstration description – visualisation of robust adaptation strategies. Available: http://www.topdad.eu/publications. [Accessed 21 March 2016].

Hinkel, J. & Bisaro, A. 2014. Methodological choices in solution-oriented adaptation research: a diagnostic framework. *Regional Environmental Change*.

Kasprzyk, J.R., Nataraj, S., Reed, P.M. & Lempert, R.J. 2013. Many objective robust decision making for complex environmental systems undergoing change, *Environmental Modelling & Software* 42(April 2013): 55-71.

Lempert, R.J., Groves, D.G. 2010. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technological Forecasting and Social Change*, 77(6):960-974.

Lempert, R.J., Groves, D.G., Popper, S.W. & Bankes, S.C. 2006. A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios. *Management Science* 52(4): 514-528.

Linkov, I., Satterstrom, F.K., Kiker, G., Batchelor, C., Bridges, T. & Ferguson, E. 2006. From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications. *Environment International*, 32: 1072–1093.

Montibeller, G. & Franco, A. 2010. *Multi-Criteria Decision Analysis for Strategic Decision Making*. Chapter 2. In Zopounidis C, Pardalos PM (eds.) (2010) Handbook of Multicriteria Analysis, Applied Optimization 103. Springer-Verlag, Berlin Heidelberg.

Salo, A. & Hämäläinen, P. 2010. *Multicriteria Decision Analysis in Group Decision Processes*. In: Greco S, Ehrgott M, Figueira JR (2010) Trends in Multiple Criteria Decision Analysis. Springer.

Scrieciu, S.Ş., Belton, V., Chalabi, Z., Mechler, R. & Puig, D. 2014. Advancing methodological thinking and practice for development-compatible climate policy planning. *Mitigation and Adaptation Strategies for Global Change* 19(3): 261-288.

Simon, H.A. 1956. Rational Choice and the Structure of the Environment. *Psychological Review* 63: 129–138.

Triantis, A.J. 2003. *Real Options*. In Handbook of Modern Finance, ed. Logue D, Seward J (New York: Research Institute of America) D1-D32.

Tufte, E.R. 1983. *The visual display of quantitative data*. Cheshire, CT: Graphics.

APPENDIX

The SRVM method can be formalized as follows:

Sc_i scenario i
St_j strategy j

$\bar{\mathbf{v}}_{ij}^{\wedge}$ optimistic performance valuations (multiple criteria or indicators) of strategy j under scenario i

$\bar{\mathbf{v}}_{ij}^{\vee}$ pessimistic performance valuations (multiple criteria or indicators) of strategy j under scenario i

$\left(\mathrm{Sc}_i, St_j\right) \rightarrow \bar{\mathbf{v}}_{ij}$ is a mapping of a scenario & strategy –combination to multiple performance levels or valuations which are uncertain (a random vector that obtains realizations from model runs or experts' opinions)

A set of robust strategy is such that the following conditions are met: $\left\{\mathrm{j} : \bar{\mathbf{v}}_{ij}^{\wedge} > \bar{\mathbf{0}} \text{ and } \bar{\mathbf{v}}_{ij}^{\vee} > \bar{\mathbf{0}} \quad \forall i\right\}$

meaning that a robust strategy outperforms the current strategy given any scenario and related optimistic and pessimistic valuations across the decision criteria.

Publication VI

Hanski, J., Rosqvist, T., and Crawford-Brown, D.
Assessing climate change adaptation strategies – case of drought and heatwave in the French nuclear sector

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Title: Assessing climate change adaptation strategies – the case of drought and heat wave in the French nuclear sector

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Abstract:

Nuclear energy is a very important component of overall power supply in France. If the effects of future extreme weather events or climate shifts are not addressed, energy systems will be highly vulnerable to extreme weather events or shifts in weather patterns, such as changes in precipitation. Because of the deep uncertainties involved in climate projections and response strategies, any strategy implementation should perform adequately regardless of which scenario actually materializes.

In this paper, we analyse the effects of drought and heat wave in the French nuclear energy sector using the Strategy Robustness Visualisation Method. The key feature of the method is the modelling of uncertainty of the quantitative indicators by {min, max}-values plotted on radar plots such that each strategy option's performance can be visually inspected for robustness. The method can be utilised as a 'module' of its own in different uncertainty management approaches. Based on the case study, the presented adaptation strategies "Maintaining industrial production and final demand" and "Smart grid infrastructure" were more robust than the "No planned or automatic adaptation".

Keywords: Climate change, adaptation, strategy assessment, French, nuclear energy

Length of manuscript:

- The number of words, counting from the top of the title page, including abstract, keywords and acknowledgements to the end of text (before the reference list): 5181 words
- 5 figures or tables (300*5=1500 words)

1. Introduction

Reducing GHG emissions from the energy sector has been a fundamental part of the European Union's climate change strategies (policies), but the need for adaptation strategies is also recognised (European Commission 2013). The importance of adaptation strategies is highlighted because the effects of climate change are likely to occur even if global mitigation targets are met (Swart et al. 2009). If the future extreme weather events or climate shifts are not addressed, energy systems will be highly vulnerable to extreme weather events or shifts in weather patterns, such as changes in precipitation (Aaheim et al. 2013). The efficiency of electricity generation may be significantly reduced by climate change, due to decreased availability of water for cooling power stations during periods of drought, and restrictions on the return of water to rivers that already at a high temperature due to extended heat waves (Aaheim et al. 2013, European Commission 2013). In addition, extreme weather periods such as heat waves and droughts will lead to increasingly significant demand peaks, potentially causing demand-driven overstress of energy infrastructure (European Commission 2013). The European Commission (2013) assessed the expected impacts on thermal power plants (including nuclear) to be medium negative by 2025 and extremely negative by 2080.

Nuclear energy is a very important component of the power supply of France, and any reduction in the ability of nuclear facilities to withdraw coolant water at sufficiently low temperature from rivers - and then return it to the rivers - will reduce the power available to the production activities of economic sectors. The energy system is a key part of the French economic system, which depends on reliable and affordable energy. Because of the long life cycles of energy infrastructure, investments in a climate-resilient energy system should be made before climate change affects the availability of water, in order to make the investments robust against climate scenarios. According to modelling results (Perrels et al. 2015), significant changes in vulnerability begin under both RCP 4.5 and 8.5 nearer to 2050 than 2100, and therefore investments in a climate-resilient energy system must be in place soon after 2050. Additionally, the year 2100 was selected as the final year of the analysis, because it is at the outer edge of available climate projections (OFGEM 2011).

Climate change can be considered as a change that introduces deep uncertainties. Under such conditions, calculations of expected values of objectives and constraints may not suffice to characterize the state of knowledge. (Kasprzyk et al. 2013). In a situation involving deep uncertainty, decision makers do not know or cannot agree upon the full set of risks to a system or their associated probabilities (Lempert and Groves 2010, Kasprzyk et al. 2013). Thissen et al. (2017) introduced three alternative approaches to planning under deep uncertainty: resilience, robustness and exploratory modelling approaches. When considering climate change adaptation, there is a need for robust strategies (Hanski and Rosqvist 2016, Kasprzyk et al. 2013, Berkhout et al. 2013). Lempert et al. (2006) defined a robust strategy as a strategy that, in comparison to the alternatives, performs relatively well across a wide range of plausible futures.

Scenario analysis explores in a logical and internally consistent manner how the future may, could or should evolve from the past and present (van der Heijden, 1996). In other words, scenario analysis explores different alternative future states (e.g. Refsgaard et al. 2007). Several different types of scenarios such as qualitative, quantitative, baseline and policy exist (Alcamo 2001, Refsgaard et al. 2007). The role of stakeholder engagement is highlighted in policy-making. Stakeholders identify and clarify policy solutions and play a key role in policy learning (McAllister et al. 2014). Pielke and Sarewitz (2005) called for more focus on the integrated and multidisciplinary aspects of climate impacts and the information needs of decision makers.

Additionally, adaptive management is an alternative for robust strategies in response to uncertainty. It aims to enhance the resilience of systems by flexible, learning-oriented and experimental management (Fritsch 2017). In adaptive management, the strategies are based on current knowledge, predicted conditions, and objectives, but must be flexible for adaption to future conditions as these emerge, thereby promoting a continual learning process (Hamilton et al. 2013).

There is still a need for methods that consider uncertain futures, deep uncertainty, scenarios, robustness and adaptation perspectives (Maier et al. 2016). There are a wide range of methods available for supporting uncertainty management, such as expert elicitation, Monte Carlo analysis, multiple model simulation, scenario analysis, sensitivity analysis and stakeholder involvement (e.g. Refsgaard et al. 2007). The need for methods for assessing the robustness of adaptation strategies is emphasized in many studies (e.g. Whateley et al. 2014, Lempert et al. 2006).

In order to meet this need, we introduce a method that is capable of visually demonstrating the robustness of adaptation strategies and can include multiple decision criteria. The Strategy Robustness Visualisation Method (SRVM) combines Multi-Criteria Decision Analysis (MCDA) and Robust Decision-Making (RDM) methodologies. SRVM can be adopted as a part of a complex and evolving process of informing governance under uncertainty. It involves uncertainty management elements such as stakeholder participation, scenario writing and adaptive management.

From the scientific perspective, the paper provides a new method for *visualizing the robustness* of adaptation strategies. The method combines quantitative modelling-based information with expert opinion and visualizes the results into radar plots. It is capable of visualizing the performance levels of a large number of decision criteria. Additionally, the reliability of the method is increased by presenting a case study using the method. The main goal of the case is to validate the method.

From the managerial perspective, the method can be utilised to increase the robustness of adaptation strategies. The case study combines results from the ARIO-model with expert opinion for a comprehensive understanding of the complex decision situation related to adaptation in the French energy sector.

In this paper, we test the method by presenting a case study for analysing the effects of drought and heat wave in the French nuclear energy sector and for assessing the alternative adaptation strategies to respond to them. The adaptation strategies are assessed particularly from the perspective of their robustness. The case deals with the possible reduction in nuclear power output during periods of extreme drought and heat in France. This paper extends the decision support methodology presented in Hanski et al. (2015) and Hanski and Rosqvist (2016) with a detailed case study.

2. Methodology

There are several complementary methods that can be used in supporting climate change related decision-making (e.g. Hinkel and Bisaro 2014). Cost-Benefit Analysis (CBA) has been the dominant methodology (Scrieciu et al. 2014). However, there are several examples of other approaches, such as Multi-Criteria Decision Analysis (MCDA) or Robust Decision-Making (RDM), which have been successfully used in climate change related decision-making (e.g. Lempert and Groves 2010, Porthin et al. 2013). The method is in line with the approach of Miller and Belton (2014), which emphasizes the importance of iterative planning processes and adjustment of alternative adaptation strategies and policies when conditions change. Additionally, it is one contribution fulfilling the proposal in Berkhout et al. (2014) that different ways of representing climate change and risks should be matched to actor frames and decision contexts.

The case study presented in this paper utilises a Strategy Robustness Visualisation Method (SRVM) to support complex long-term decision situations (Hanski and Rosqvist 2016, Hanski et al. 2015). This is only the second case study using SRVM, and the method should be applied in other case studies in order to increase its reliability. SRVM is based on combined RDM and MCDA methods. The key feature of the SRVM is modelling of uncertainty of the quantitative indicators by {min, max}-values plotted on radar plots such that each strategy option's performance, under each scenario, can be visually inspected for robustness (see Appendix 1).

The SRVM follows MCDA in terms of performance modelling, but limits measurement to single criteria that remain separated, without combining the criteria into a single utility measure by an additive utility function. Similarly to RDM, SRVM does not assign probabilities to scenarios but describes the few scenarios in such detail that it enables the experts to give an opinion about the performance of the strategies under each scenario (Hanski and Rosqvist 2016).

In the method, the decision context, decision criteria and adaptation strategies are developed in cooperation with the stakeholders in an iterative process. The method can be used to visualise and evaluate the vulnerability of alternative adaptation strategies and to show the key trade-offs between the strategies to decision-makers. The case study was conducted from early 2015 to late 2015. The method consists of seven iterative phases as shown in Fig 1.

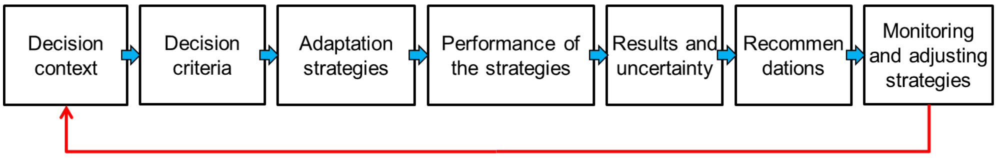

Fig. 1 SRVM supports complex climate change adaptation decisions under deep uncertainty

1. **Decision context**. Identification of the stakeholders and all the important factors affecting the decisions, and selecting and involving the relevant stakeholders in the process. Learning from the successes and failures of past strategies (policies) (e.g. Schmidt and Radaelli 2004). Selection or creation of qualitative baseline and policy scenarios (scenario combinations) to test the performance of the strategies (e.g. Alcamo 2001).
2. **Decision criteria**. Selection of the most important decision criteria for the strategies.
3. **Adaptation strategies**. Selection of the most important strategies to be assessed within the decision context.
4. **Performance of the strategies**. Assessment of the adaptation strategies against each decision criterion, under all specified scenarios.
5. **Results and uncertainty**. Visualization of the performance of strategies, with uncertainty ranges specified by the {min,max}-pairs of pessimistic and optimistic performance, using radar plots.
6. **Recommendations**. Identification of the robustness, or non-robustness (vulnerability) and the key uncertainties of the strategies.
7. **Monitoring and adjusting strategies.** Reviewing implemented strategies as the decision context changes.

SRVM is used to visualize robustness in a multi-criteria assessment situation, especially in long-term decision-making in which several futures can be envisaged. For defining robust strategies we use the definition presented in Hanski and Rosqvist (2016): "a strategy is robust if its deviation from the current strategy is positively valued across the range of impact criteria under the given scenarios". A robust strategy can be described as a low-regret strategy that performs adequately in most future conditions envisioned in the scenarios, where low-regret strategies are those strategies that are insensitive to both short- and long-term scenarios. The selection of low-regret strategies is ultimately made by decision-makers based on the visualizations and other available data.

Performance of the strategies cannot always be modelled by formal methods, such as simulation. Furthermore, the subjective opinions of experts are needed for comprehensive assessments, especially as these relate to decision criteria. SRVM uses only minimum and maximum values if value distributions of the performances are available. For the

visualisation of robustness of performance with respect to several criteria, the radar plot technique was selected (see

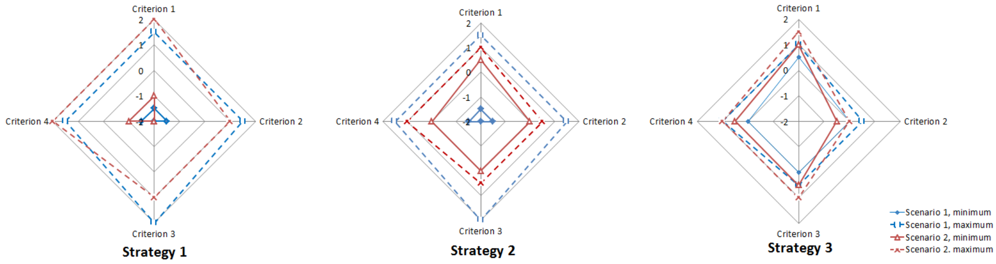

Fig. 2).

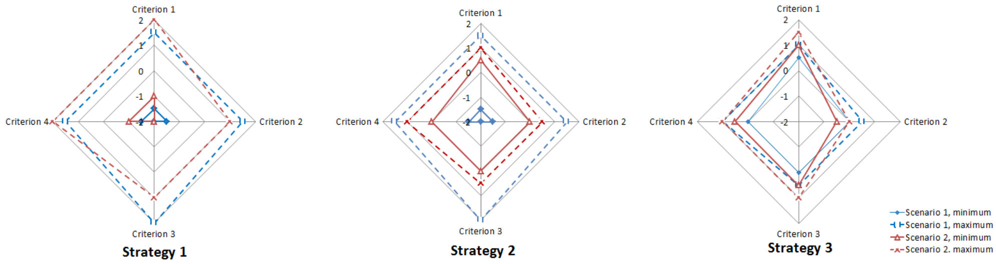

Fig. 2 Illustration of the results produced by SRVM under two different scenarios

Visually, robustness of adaptation strategies is shown by several line-pairs which are close to each other for all scenarios (Hanski and Rosqvist 2016). According to Montibeller and Franco (2010), visual inspection of performance is found to be the most helpful way of supporting the choice of robust strategies. The radar plots above illustrate a hypothetical decision situation in which three strategies are compared using four decision criteria. The uncertainty that has been presented in the form of probability density function (pdf) is reduced to the two samples of pdf in order for the visualization to be feasible. Percentiles 0.05/0.01 and 0.95/0.99 would be adequate to represent the variance for the purpose of identifying robustness. The solid lines describe the minimum performance received from the modelling or expert opinion, whereas the dotted lines represent the maximum. The minimum represents either the 0.05 percentile of the performance in the case of modelling, or the minimum scores from the valuation of stakeholders, whereas the maximum represents the 0.95 percentile or the maximum scores, respectively. The strategies are compared to a baseline producing a major increase (+2), no change (0) or a major decrease (-2) of performance of the energy system with regard to these criteria. In Strategy 1, employing visual inspection, there is a considerable variance in the minimum and maximum performance, but the performance is rather similar in both scenarios. In Strategy 2, there is a high variance in the performance in scenario 1, but scenario 2 shows only a low level of variance. In Strategy 3, the variance between the scenarios and the minimum and maximum performance values is low. Therefore, Strategy 3 could be called robust, at least in comparison to the other strategies.

3. Effects of drought and heat wave on the French nuclear energy sector

Decision context

The case considers the possible reduction in nuclear power output during periods of extreme drought and heat in France. Since nuclear power represents a high percentage of the overall power supply of France, any reduction in the ability of nuclear facilities to withdraw coolant water at sufficiently low temperature from rivers – or to reject coolant water back into those rivers after use - will reduce the power available to the production activities of economic sectors. The energy system of France is a key component of the economic system; a vibrant economy depends on a reliable and affordable energy system. Therefore, the case examines how curtailment of the energy system due to extreme weather would 'ripple' through the economy, producing indirect economic effects that could in some cases be as large as the direct impacts on the energy system.

Analysis of the economic impacts was carried out using the Adaptive Regional Input-Output (ARIO) model of the Cambridge Centre for Climate Change Mitigation Research (Crawford-Brown et al. 2013; Li et al. 2013). The model divides the French economy into 35 economic sectors from the World Input-Output Database, including the energy sector. Changes to both demand and supply of energy cause changes in the production capacity of the non-energy sectors such as manufacturing, in turn influencing the GDP of the overall economy. These changes become progressively smaller as the initial damage to the energy system, caused by a combined drought and heat wave, dissipate over time. In this case study, it is assumed that there is no long-term damage to the nuclear plant, only a temporary curtailment of power production.

Current climate scenarios reflect the projected decline in summer/spring precipitation, and the consequent reduced run-off to rivers in catchment areas, potentially reducing volumetric flow rates in rivers and increasing the temperature of water in the river, which in turn will affect the permitted abstraction and release rates of water from power plants. This could result in the partial shutting down of power production during extreme periods of drought leading to low water flow, exacerbated by water temperature increase when the drought is accompanied by a heat wave. The impact of a changing precipitation rate and ambient air temperature – as provided by the climate modelling component of the ToPDAd project – are normalised to historical data on the climatic conditions that led to the 2003 drought and heat wave that affected nuclear power production. Curtailments of power production during the scenarios of the present study were based on the number of days when drought and/or temperature were more severe than in the 2003 case.

Performance evaluations were obtained from representatives of three stakeholder groups: EdF, Eon and National Grid (UK). The three interviewees provided the scores for the separate criteria under the scenarios and adaptation strategies. These scores reflect judgments by the survey participants of the post-2003 changes to the nuclear power system and regulatory requirements that were introduced to improve performance under conditions of drought and heat. The scores were then fed into a Microsoft Excel-based program to generate the results presented in the figures that follow.

For the case, two adaptation strategies are selected and compared to a baseline of "no planned or automatic adaptation" strategy. The adaptation strategies consider two time horizons, 2050 and 2100. The scenario combinations support the decision-makers in their evaluations and are used as input data in modelling the performance of the adaptation strategies. They are based on Representative Concentration Pathways (RCPs) and Socio-economic Pathways (SSPs). RCPs describe greenhouse gas concentrations and provide guidelines to emission projections, and SSPs describe global socio-economic development trajectories. The RCPs in turn modify the number of days of low rainfall (drought) and high ambient air temperature (influencing ambient water temperature in rivers used for coolant water – no impact on coastal cooling is assumed). For the case, RCP 2.6 and RCP 8.5, and SSP 1 and SSP 5 are selected, because these combinations represent the plausible extreme ends of climate and socio-economic predictions (Harjanne et al. 2014). In addition to the two extreme scenario combinations a baseline scenario was selected. The detailed scenario assumptions are as follows:

- *Baseline*. This refers to a future climate and socio-economic condition in 2050 that is basically similar to the current conditions. The baseline does not include climate change impacts and does not match any expected climate development. It is used to distinguish the impact of climate change and general socio-economic development from specific impacts due to changes in the future energy system.
- *Low climate change (RCP2.6+SSP1)*. The low climate change scenario is a sustainability-oriented, open and cooperative world with low adaptation needs. Global GHG emissions peak during the 2010s and decline substantially thereafter. Inequality both between countries and within economies is

decreased as low-income areas develop rapidly. Technological development is also rapid. Economies are globalized and open, with strict environmental protection policies. This scenario assumes moderate to small climate effects and worldwide cooperation ensuring electricity supply connections. Energy and resource efficiency are emphasised, leading to lower overall energy demand.

- *High climate change (RCP8.5+SSP5)*. High climate change scenario represents a growth-oriented world with low regulation. There are high adaptation needs compared to the baseline, and global GHG emissions continue to increase throughout the 21st century. The world has chosen conventional fossil-fuel dominated development due to pressures from social and economic factors. This maintains faster economic growth across the world and helps to create resources for adapting to the climate change impacts, but does not lead to ambitious mitigation targets. Compared to the low climate scenario, the high climate change scenario is an extension of business-as-usual, leading to stronger climate impacts. Centralised, mainly fossil-based electricity production remains as the most important production form globally, although nuclear remains dominant in France. Other electricity generation forms are also important, especially in regions where they have become competitive or where there are strong supporting policy measures.

Decision criteria

In this phase the decision criteria and their scale are selected. The following criteria are thought by the stakeholders and researchers to be the most important:

- *Peak power loss.* Average loss of power generation capacity in the entire grid due to the drought/heat wave over the first week of the extreme weather event
- *Meeting final demand.* The cumulative gap (percentage of MWh of demand) between supply and demand during the entire extreme weather event
- *Service to critical industries.* The cumulative gap (percentage of MWh of demand) met for industries that are critical for GDP production
- *Power available for export*. The total amount of power (MWh) provided to the export sector of the economy for sale elsewhere in the EU
- *Water availability for agricultural use*. The extent to which water might be redirected from agriculture to power plants in a water basin during the period of the extreme weather event

For each decision criterion, we provide a specification of where the information needed to judge the performance of an adaptation strategy was obtained in the case (from modelling, other published research or expert opinion), and a scale for making the necessary judgment. Modelling results using the ARIO model were the source of information for the first three decision criteria, whereas the performance of the last two criteria was determined by expert opinion. The 2003 and 2006 heat waves/droughts were utilised as input for the modelling. A five step scale (-2…+2) was chosen due to the limited resolution in the modelling and to make it easier for the stakeholders to evaluate the future performance of the strategies (Appendix 2).

Adaptation strategies

Two adaptation strategies and a “no planned or automatic adaptation” strategy are considered in the analysis. These strategies were preselected by the authors and were considered the most relevant strategies by the interviewed experts. The used model also set limitations for the selection of adaptation strategies. However, in the future, other adaptation strategies relevant for the decision situation could emerge. Each is designed to reduce the total economic losses due to curtailment of nuclear power production during extreme droughts/heat waves. The following strategies were assessed:

- *No planned or automatic adaptation*. Effects of climate and socio-economic change without planned or automatic adaptation.
- *Maintaining industrial production and final demand*. Residual power during a period of power curtailment is allocated in order to preferentially maintain industrial production and meet final

consumer demand (for power) in France, accompanied by a reduction in power available for exports. Example: Residual power is allocated preferentially to both the economic sectors producing the greatest contribution to GDP, and to those firms that could cause bottlenecks in industrial production even if they themselves are not directly significant contributors to GDP.

- *Smart grid infrastructure*. Residual power is allocated to maintain industrial production, final demand and exports, with a smart grid and smart buildings introduced to allow for reduction of non-essential energy use during the 'brown outs'. Example: The national grid is altered to include 'smart grid' connections to end users, with power contracts in place to allow the grid operator to re-allocate reduced residual power to operations that (1) cannot be curtailed without significant loss of service to end users and (2) are significant contributors to GDP.

Performance of the strategies

In this phase, each adaptation strategy is assessed against each decision criterion, under all specified scenarios in turn. The method only uses two value-pairs from the value distributions, which can be called optimistic (max) and pessimistic (min) values. The value-pairs represent the variance in the performance of strategies. In the example below, the average values are also given but they are not used in the assessment of robustness. In the case of a distribution of values, the percentiles 0.05 and 0.95 are associated with pessimistic and optimistic, respectively. Similarly, the variation of expert opinions based on their specified decision criteria is reduced to pessimistic and optimistic values by taking the minimum and maximum scores.

The performance of the adaptation strategies regarding all the decision criteria is depicted in Appendix 3. The distribution and the averages are presented for both scenarios. Based on the scales presented in Appendix 2, the performances of the decision criteria are converted to a -2…2 scale as depicted in Appendices 4 and 5.

Results and uncertainty

The performance of adaptation strategies is presented in Figs. 3, 4 and 5 using radar plots to present the robustness of the strategies. The uncertainty is shown by plotting two similar-colour lines; one linking the minimum values, and the other linking the maximum values of the decision criterion. The higher up the arms of the radar plot the line is, the higher is the positive performance. For example, in case of peak power loss, higher performance means lower peak power loss. As uncertainty increases, the distance between these two lines increases. In this type of visualisation, each scenario line pair is plotted on the same radar plot. Robustness is shown by closeness of the line-pairs to each other for all scenarios. Strategies that are insensitive to both short- and long-term scenarios are so-called 'low-regret' strategies. In addition, the plot can also be used for ranking. The higher the score, the higher is the performance.

In general, all the performance scores in all the strategies are expected either to be worse or to remain unchanged. The adaptation strategies "Maintaining industrial production and final demand" and "Smart grid infrastructure" fare better than the "No planned or automatic adaptation" strategy both in 2050 and in 2100, as the performance scores of the latter strategy are further away from the centre of the radar plot. As expected, the performance of strategies in high climate change scenario is, in general, lower than that in the low climate change scenario. Especially the minimum performance results of the strategies "Maintaining…" and "Smart…" are higher than that of the "No planned…" strategy, signalling a possibility of low-regret strategies.

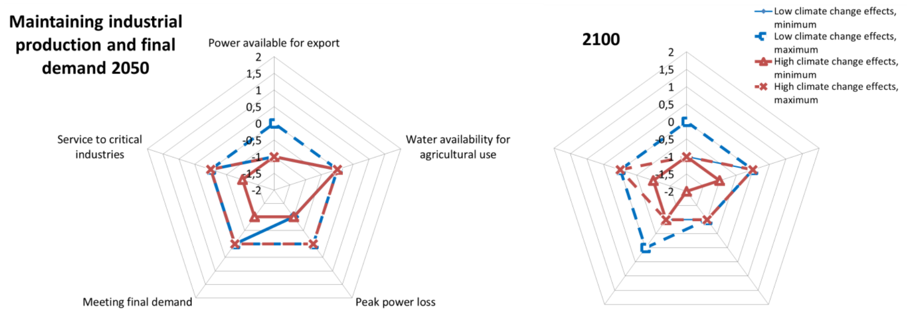

Fig. 3 Visualisation of the robustness of the strategy "Maintaining industrial production and final demand" in the years 2050 and 2100 compared to the baseline

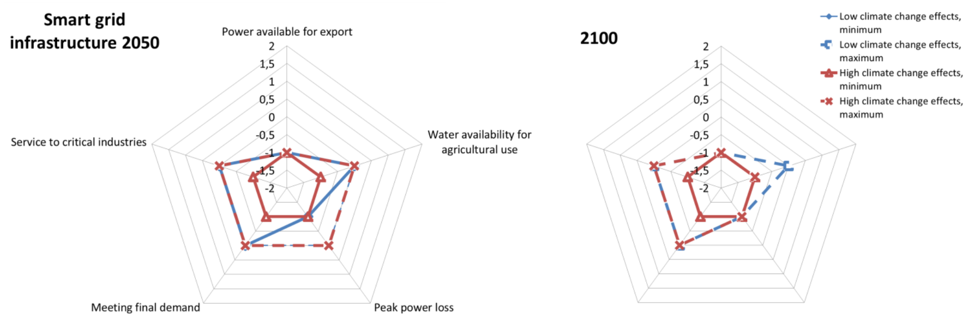

Fig. 4 Visualisation of the robustness of the strategy "Smart grid infrastructure" in the years 2050 and 2100 compared to the baseline

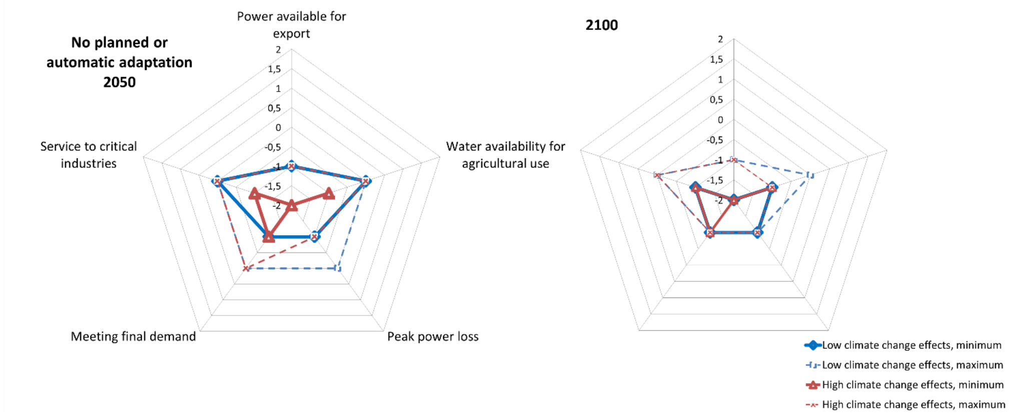

Fig. 5 Visualisation of the robustness of the strategy "No planned or automatic adaptation" in the years 2050 and 2100 compared to the baseline

4. Discussion and Conclusions

The case study presented in this paper considers the possible reduction in nuclear power output during periods of extreme drought and heat in France. Because of the importance of nuclear energy to the French economy, any reduction in production has significant effects on the French economy. We argue that robustness is a key criterion in analysing the long-term performance of energy sector strategies. Using SRVM, two adaptation strategies "Maintaining industrial production and final demand" and "Smart grid infrastructure" and a "No planned or automatic adaptation" strategy were analysed regarding their robustness. According to the results, both adaptation strategies appeared to be more robust than the "No planned or automatic adaptation" strategy. Therefore, we suggest the implementation of adaptive management (e.g. Fritsch 2017; Hamilton et al. 2013) to develop and maintain the French energy system.

To support the implementation phase, we suggest the identification of implementation actions that are common for both basic strategies. Additionally, we suggest the identification of the options for combining or changing the adaptation strategies as new knowledge of future conditions emerges. More research is needed in combining adaptive management principles to robustness and SRVM.

The selected case was used for demonstration and did not directly lead to decisions, although real stakeholders were involved in the case. However, the authors and stakeholders generally agreed that the methodology improved the understanding of the decision-makers in complex climate change adaptation related decision-making situations.

The main goal of the case study was to validate the method. In the method, the robustness and vulnerability of the selected strategies is assessed using modelling and stakeholder-based information. The case study utilises information from two sources; modelling information from the ARIO model and expert opinion from stakeholders. Additionally, both quantitative and qualitative scenarios are utilised in the study. The ARIO model uses quantitative scenario combinations as an input, whereas the stakeholders use case-specific qualitative descriptions of the different scenario combinations to support their performance assessments. The qualitative case-specific descriptions have been found by the stakeholders to be helpful.

The radar plot was selected as the visualization technique for this case study. In the case study, the robustness of the adaptation strategies is not as clearly visible as in the illustrative cases presented in Fig. 2. The illustrative cases present ideal cases of robustness, and in practical applications of SRVM the radar plots will need more extensive interpretation for supporting decisions. However, other visualization techniques such as bar charts could also be used. Testing the pros and cons of other visualization techniques needs further research.

Limitations of this research stemmed from case study methodology, expert judgment and the scales used for performance assessment. The presented case was the second case assessed with SRVM methodology (Hanski and Rosqvist 2016, Hanski et al. 2015). Further research is needed to validate the SRVM and assess its strengths and weaknesses.

The SRVM supposes that experts' judgments do not lead to disagreement on the min- and max-estimates of the performance criteria. If disagreement exists, more information is needed until the discrepancy is settled. Additionally, in some cases when experts estimate probabilities, they tend to fix on an initial value and then adjusting it (Cooke, 1991). In this case, the resulting value may be biased towards the initial value (Skjong and Wentworth, 2001).

In this case study, a five step scale (-2…+2) was chosen due to the limited resolution in the modelling and to make it easier for the stakeholders to evaluate the future performance of the strategies. However, a more extensive scale could be used in other decision contexts.

In conclusion, we argue that the SRVM can be a helpful method for policy learning regarding complex issues where decision-making is conducted under deep uncertainty. Assessing the robustness of adaptation strategies gives the decision-makers an idea of low-regret strategies; i.e. strategies that are justified under most, if not all, scenarios. The method highlights the importance of engaging stakeholders and decision-makers in the scenario process, and of visualisation of the results. Our key contribution to the identification of robustness by visual inspection can be utilised as a 'module' of its own in different uncertainty management approaches, such as described by Refsgaard et al. (2007) and van der Sluijs et al. (2005). As a process, SRVM is closer to decision and scenario analysis than risk analysis, in which the probabilities of the scenarios are assessed, affecting the choice of strategies.

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References

Aaheim A, Crawford-Brown D, Axhausen KW, Ciari F, Stahel A, Perrels A, Nurmi V, Pilli-Sihvola K, Meyer B, Prettenthaler F, Richter V, Purwanto AJ, Heyndrickx C, Osborn T, Wallace C, Warren R, Jantunen J, Molarius R, Nokkala M (2013) Sector-level adaptation challenges in the literature. ToPDAd deliverable 1.1. Available: http://www.topdad.eu/upl/files/98434. Accessed December 2015.

Alcamo J (2001) Scenarios as Tools for International Environmental Assessments. European Environment Agency, Copenhagen. Environmental Issues Report. Experts Corner Report. Prospects and Scenarios No. 5.

Berkhout F, Bouwer L, Bayer J, Bouzid M, Cabeza M, Hanger S, Hof A, Hunter P, Meller L, Patt A, Pfluger B, Rayner T, Reichardt K, van Teeffelen A (2013) European responses to climate change: Deep emissions reductions and main-streaming of mitigation and adaptation. Key findings of the European Commission FP7 RESPONSES project. Policy Brief.

Berkhout F, van den Hurk B, Bessembinder J, de Boer J, Bregman B, van Drunen M (2014) Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments. Reg Environ Change (2014) 14:879–893. doi: 10.1007/s10113-013-0519-2

Cooke RM (1991) Experts in Uncertainty - Opinion and Subjective Probability in Science. Oxford University Press, New York. ISBN-10: 0195064658

Crawford-Brown D, Syddall M, Guan D, Hall J, Li J, Jenkins K, Beaven R (2013) Vulnerability of London's economy to climate change: Sensitivity to production loss. *Journal of Environmental Protection* 4:548-563. doi: 10.4236/jep.2013.46064

European Commission (2013) Adapting infrastructure to climate change. Commission Staff Working Document, SWD 137. Available: http://ec.europa.eu/clima/policies/adaptation/what/docs/swd_2013_137_en.pdf. Accessed December 2015

Fritsch O (2017) Integrated and adaptive water resources management: exploring public participation in the UK. *Reg Environ Change,* 17:1933-1944. doi: 10.1007/s10113-016-0973-8

Hamilton MC, Thekdi SA, Jenicek EM, Harmon RS, Goodsite ME, Case MP, Karvetski CW, Lambert JH (2013) Case studies of scenario analysis for adaptive management of natural resource and infrastructure systems. *Environmental Systems & Decisions,* 33:89–103. doi: 10.1007/s10669-012-9424-3

Hanski J, Rosqvist T (2016) A method for visualisation of uncertainty and robustness in complex long-term decisions. In: Risk, Reliability and Safety: Innovating Theory and Practice, pp.2929-2936. doi: 10.1201/9781315374987-445

Hanski J, Rosqvist T, Crawford-Brown D (2015) ToPDAd deliverable D4.3 - Demonstration description – visualisation of robust adaptation strategies. Available: http://www.topdad.eu/publications. Accessed October 2015

Harjanne A, Nurmi V, Perrels A,Votsis A, Osborn T, Melvin T, Wallace C (2014) ToPDAd deliverable D2.1 - Climate hazard and impact scenarios. Available: http://www.topdad.eu/publications. Accessed October 2015

van der Heijden K (1996) *Scenarios: The Art of Strategic Conversation*. John Wiley & Sons.

Hinkel J, Bisaro A (2014) Methodological choices in solution-oriented adaptation research: a diagnostic framework. Reg Environ Change. doi:10.1007/s10113-014-0682-0.

Kasprzyk JR, Nataraj S, Reed PM, Lempert RJ (2013) Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling & Software* 42:55-71. doi: doi.org/10.1016/j.envsoft.2012.12.007

Lempert RJ, Groves DG (2010) Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technological Forecasting and Social Change* 77(6):960-974. doi: doi.org/10.1016/j.techfore.2010.04.007

Lempert RJ, Groves DG, Popper SW, Bankes SC (2006) A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios. *Management Science* 52(4): 514-528. doi: 10.1287/mnsc.1050.0472

Li J, Crawford-Brown D, Syddall M, Guan D (2013) Modeling imbalanced economic recovery following a natural disaster using input–output analysis. *Risk Analysis* 33:1908-1923. doi: 10.1111/risa.12040

Maier HR, Guillaume JHA, van Delden H, Riddell GA, Haasnoot M, Kwakkel JH (2016) An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software*, 81:154-164. doi: 10.1016/j.envsoft.2016.03.014

McAllister RRJ, McCrea R, Lubell MN (2014) Policy networks, stakeholder interactions and climate adaptation in the region of South East Queensland, Australia. *Reg Environ Change*, 14:527-539. doi: 10.1007/s10113-013-0489-4

Miller KA, Belton V (2014) Water resource management and climate change adaptation: a holistic and multiple criteria perspective. *Mitigation and Adaptation Strategies for Global Change* 19(3):289-308. doi: 10.1007/s11027-013-9537-0

Montibeller G, Franco A (2010) Multi-Criteria Decision Analysis for Strategic Decision Making. Chapter 2. In Zopounidis C, Pardalos PM (eds.) (2010) Handbook of Multicriteria Analysis, Applied Optimization 103. Springer-Verlag, Berlin Heidel-berg. doi: 10.1007/978-3-540-92828-7_2

OFGEM (2011) Adaptation to Climate Change. Report to DEFRA, Office of the Gas and Electricity Markets. London.

Perrels A (Ed.), Prettenthaler F, Kortschak D, Heyndrickx C, Ciari F, Boesch P, Kiviluoma J, Azevedo M, Ekholm T, Crawford-Brown D and Thompson A (2015). ToPDAd deliverable D2.4. Available: http://www.topdad.eu/publications. Accessed 13 April 2016

Pielke RA, Sarewitz D (2005) Bringing Society Back into the Climate Debate. *Popul Environ* 26: 255-268. doi: 10.1007/s11111-005-1877-6

Porthin M, Rosqvist T, Perrels A, Molarius R (2013) Multi-criteria decision analysis in adaptation decision-making: a flood case study in Finland. *Regional Environmental Change* 13(6):1171 – 1180. doi: 10.1007/s10113-013-0423-9

Refsgaard JC, van der Sluijs JP, Højberg AL, Vanrolleghem PA (2007) Uncertainty in the environmental modelling process – A framework and guidance. *Environmental Modelling & Software* 22(11):1543-1556. doi: 10.1016/j.envsoft.2007.02.004

Schmidt VA, Radaelli CM (2004) Policy change and discourse in Europe: conceptual and methodological issues. West *Eur Polit* 27:183–210. doi: 10.1080/0140238042000214874

Scrieciu SȘ, Belton V, Chalabi Z, Mechler R, Puig D (2014) Advancing methodological thinking and practice for development-compatible climate policy planning. *Mitigation and Adaptation Strategies for Global Change* 19(3):261-288. doi: 10.1007/s11027-013-9538-z

Skjong R, and Wentworth B (2001) Expert judgement and risk perception. Proceedings of the Eleventh International Offshore and Polar Engineering Conference Stavanger, Norway, June 17-22, 2001. ISBN 1-880653-51-6.

van der Sluijs JP, Craye M, Funtowicz S, Kloprogge P, Ravetz J, Risbey J (2005) Combining quantitative and qualitative measures of uncertainty in model based environmental assessment: the NUSAP System. *Risk Analysis* 25 (2), 481e492. doi: 10.1111/j.1539-6924.2005.00604.x

Swart R, Biesbroek R, Binnerup S, Carter TR, Cowan C, Henrichs T, Loquen S. Mela H, Morecroft M, Reese M, Rey D (2009) Europe adapts to climate change: Comparing national adaptation strategies. Partnership for European Research. PEER Report 1.

Thissen W, Kwakkel J, Mens M, van der Sluijs J, Stemberger S, Wardekker A, Wildschut D (2017) Dealing with Uncertainties in Fresh Water Supply: Experiences in the Netherlands. *Water Resour Manage* 31:703-725. doi: 10.1007/s11269-015-1198-1

Whateley S, Steinschneider S, Brown C (2014) A climate change range-based method for estimating robustness for water resources supply. *Water Resour. Res.* 50:8944–8961. doi: 10.1002/2014WR015956.

Appendices

Appendix 1

The SRVM method can be formalized as follows (Hanski and Rosqvist 2016):

Sc_i scenario i

St_j strategy j

$\bar{\mathbf{v}}_{ij}^{\wedge}$ optimistic performance valuations (multiple criteria or indicators) of strategy j under scenario i

$\bar{\mathbf{v}}_{ij}^{\vee}$ pessimistic performance valuations (multiple criteria or indicators) of strategy j under scenario i

$(\mathrm{Sc}_i, St_j) \rightarrow \overline{\mathbf{v}}_{ij}$ is a mapping of a scenario & strategy –combination to multiple performance levels or valuations which are uncertain (a random vector which get values from model runs or experts' opinions)

A set of robust strategy is such that the following conditions are met: $\{j : \overline{\mathbf{v}}_{ij}^{\wedge} > \overline{\mathbf{0}} \text{ and } \overline{\mathbf{v}}_{ij}^{\vee} > \overline{\mathbf{0}} \;\; \forall i\}$

meaning that a robust strategy outperforms the current strategy given any scenario and related optimistic and pessimistic valuations across the decision criteria.

Appendix 2

Table 1 Scales for assessing the performance of the decision criteria

Decision criterion	Scale
Peak power loss	-2 decrease in peak power (more than 15% loss from baseline) -1 decrease in peak power (-5% to -15% from baseline) 0 small change (-5% to +5% from baseline) +1 increase in peak power (+5% to +15% from baseline) +2 increase in peak power (more than 15% increase from baseline)
Meeting final demand	-2 decrease in peak power (more than 15% loss from baseline) -1 decrease in peak power (-5% to -15% from baseline) 0 small change (-5% to +5% from baseline) +1 increase in peak power (+5% to +15% from baseline) +2 increase in peak power (more than 15% increase from baseline)
Service to critical industries	-2 decrease in peak power (more than 15% loss from baseline) -1 decrease in peak power (-5% to -15% from baseline) 0 small change (-5% to +5% from baseline) +1 increase in peak power (+5% to +15% from baseline) +2 increase in peak power (more than 15% increase from baseline)
Power available for export	-2 decrease (more than 20% loss from baseline) -1 decrease (-5% to -20% from baseline) 0 small change (-5% to +5 % from baseline) +1 increase (+5% to +20% from baseline) +2 increase (more than 20% increase from baseline)
Water availability for agricultural use	+2 increase (more than 20% increase from baseline) -2 decrease of water available for agriculture (more than 25% loss from baseline) -1 decrease of water available for agriculture (-5% to -25% loss from baseline) 0 small change (-5% to +5% from baseline) +1 increase of water available for agriculture (+5% to +25% loss from baseline) +2 increase of water available for agriculture (more than 25% increase from baseline)

Appendix 3

Table 2 Performance of the adaptation strategies based on ARIO modelling

	Baseline			2050 (% change from baseline)			2100 (% change from baseline)		
Peak power loss, LOW CC	**min**	**avg**	**max**	**min**	**avg**	**max**	**min**	**avg**	**max**
No planned adaptation	6 GW	4 GW	2 GW	-0,10	-0,08	-0,04	-0,12	-0,10	-0,07
Maintaining industrial production and final demand	5 GW	4 GW	2 GW	-0,06	-0,06	-0,04	-0,12	-0,08	-0,06
Smart grid infrastructure	5 GW	4 GW	2 GW	-0,06	-0,04	-0,02	-0,12	-0,08	-0,05
Peak power loss, HIGH CC									
No planned adaptation	6 GW	4 GW	2 GW	-0,15	-0,10	-0,06	-0,20	-0,15	-0,09
Maintaining industrial production and final demand	6 GW	4 GW	3 GW	-0,10	-0,07	-0,03	-0,16	-0,13	-0,08
Smart grid infrastructure	5 GW	4 GW	3 GW	-0,08	-0,05	-0,01	-0,12	-0,10	-0,06
Meeting final demand, LOW CC									
No planned adaptation	60 GW	60 GW	60 GW	-0,07	-0,05	-0,02	-0,12	-0,10	-0,06
Maintaining industrial production and final demand	60 GW	60 GW	60 GW	-0,04	-0,02	-0,01	-0,07	-0,06	-0,04
Smart grid infrastructure	60 GW	60 GW	60 GW	-0,04	-0,02	-0,01	-0,08	-0,06	-0,04
Meeting final demand, HIGH CC									
No planned adaptation	60 GW	60 GW	60 GW	-0,07	-0,05	-0,03	-0,14	-0,10	-0,07
Maintaining industrial production and final demand	60 GW	60 GW	60 GW	-0,05	-0,03	-0,02	-0,10	-0,08	-0,05
Smart grid infrastructure	60 GW	60 GW	60 GW	-0,05	-0,03	-0,02	-0,10	-0,06	-0,04
Service to critical industries, LOW CC									
No planned adaptation	100 % service	100 % service	100 % service	-0,04	-0,02	-0,01	-0,08	-0,05	-0,03
Maintaining industrial production and final demand	100 % service	100 % service	100 % service	-0,02	-0,01	-0,005	-0,05	-0,03	-0,02
Smart grid infrastructure	100 % service	100 % service	100 % service	-0,02	-0,01	-0,005	-0,05	-0,01	-0,02
Service to critical industries, HIGH CC									
No planned adaptation	100 % service	100 % service	100 % service	-0,05	-0,03	-0,02	-0,09	-0,06	-0,04

Maintaining industrial production and final demand	100 % service	100 % service	100 % service	-0,06	-0,02	-0,01	-0,06	-0,04	-0,02
Smart grid infrastructure	100 % service	100 % service	100 % service	-0,06	-0,02	-0,01	-0,06	-0,04	-0,02

Appendix 4

Table 3 Scaled modelling results

	2050			2100		
Peak power loss, LOW CC	min	avg	max	min	avg	max
No planned adaptation	-1	-1	0	-1	-1	-1
Maintaining industrial production and final demand	-1	-1	0	-1	-1	-1
Smart grid infrastructure	-1	0	0	-1	-1	-1
Peak power loss, HIGH CC						
No planned adaptation	-2	-1	-1	-2	-2	-1
Maintaining industrial production and final demand	-1	-1	0	-2	-1	-1
Smart grid infrastructure	-1	-1	0	-1	-1	-1
Meeting final demand, LOW CC						
No planned adaptation	-1	-1	0	-1	-1	-1
Maintaining industrial production and final demand	0	0	0	-1	-1	0
Smart grid infrastructure	0	0	0	-1	-1	0
Meeting final demand, HIGH CC						
No planned adaptation	-1	-1	0	-1	-1	-1
Maintaining industrial production and final demand	-1	0	0	-1	-1	-1
Smart grid infrastructure	-1	0	0	-1	-1	0
Service to critical industries, LOW CC						
No planned adaptation	0	0	0	-1	-1	0
Maintaining industrial production and final demand	0	0	0	-1	0	0
Smart grid infrastructure	0	0	0	-1	0	0
Service to critical industries, HIGH CC						
No planned adaptation	-1	0	0	-1	-1	0
Maintaining industrial production and final demand	-1	0	0	-1	0	0

Smart grid infrastructure	-1	0	0	-1	0	0

Appendix 5

Table 4 Performance of the adaptation strategies based on expert opinion

	2050			2100		
Power available for export, LOW CC	min	avg	max	min	avg	max
No planned adaptation	-1	-1	-1	-2	-1,33	-1
Maintaining industrial production and final demand	-1	-0,67	0	-1	-0,67	0
Smart grid infrastructure	-1	-1	-1	-1	-1	-1
Power available for export, HIGH CC						
No planned adaptation	-2	-1,67	-1	-2	-1,67	-1
Maintaining industrial production and final demand	-1	-1	-1	-1	-1	-1
Smart grid infrastructure	-1	-1	-1	-1	-1	-1
Water availability for agricultural use, LOW CC						
No planned adaptation	0	0	0	-1	-0,67	0
Maintaining industrial production and final demand	0	0	0	0	0	0
Smart grid infrastructure	0	0	0	-1	-0,67	0
Water availability for agricultural use, HIGH CC						
No planned adaptation	-1	-0,67	0	-1	-1	-1
Maintaining industrial production and final demand	0	0	0	-1	-0,67	0
Smart grid infrastructure	-1	-0,67	0	-1	-1	-1

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