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Technology Value Mapping (TVM)

Method for Designing Technology Value Capture by Visually Modelling Product Properties and Behaviours

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ACADEMIC DISSERTATION
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PREFACE

This dissertation was carried out on an industrial basis for, and with funding from, the Department of Mechanical Engineering of Tampere University, in cooperation with Sandvik Mining and Construction Oy's Tampere plant. The project is part of the Doctoral School of Industry Innovations (DSII) and the work was carried out from 2016–2019.

While this project was personally difficult at times, it ultimately proved rewarding. My goals for the project changed as the work progressed, starting with the idea of writing a dissertation and ending with learning the science and professional understanding behind the effects of technology, especially with the influence of my supervisor, associate Professor Tero Juuti. Evaluating my own and other people’s capacity to recognize assumptions on the basis of decisions made held particular fascination.

On behalf of Tampere University, I would like to offer special thanks to Professor Juuti, whose help was invaluable in completing this project. Along the way, there were fierce debates about the subject and on related topics between us. Thanks are also due to Dr Timo Lehtonen, another supervisor of my work and provider of new ideas and directions to take the topic. My closest colleague during the project was Dr Jarkko Pakkanen, who deserves thanks for many discussions on writing articles and various personal topics.

On behalf of Sandvik Mining and Construction Oy, I would like to thank my supervisor, MSc Pasi Julkunen, who made this work possible in many ways. Regardless of the industry’s changing situation, Pasi always provided me with the space and opportunity to continue my work, even though the subject changed several times along the way. Another very important person to the progress of my work was Pauli Lemmetty, whose extensive experience provided me with information on the behaviour of both the target company's technical product and the organization.

Finally, I would like to thank my family, who made it possible for me to pursue my studies at length and provided support whenever needed.

ABSTRACT

The purpose of this thesis is to develop and introduce a new technology valuation method for concept development phase. The aim is to support the evaluation and valuation of new technologies, particularly in terms of improving the reliability and cost-effectiveness of technology valuation. A constructive research approach and design research methodology (DRM) were used in the research and method development of this thesis. The presented technology valuation method was evaluated and developed through three case studies in the mining industry.

This thesis contributes to technology valuation by increasing understanding and providing tools for modelling the effects of technology through the product. To understand the effects of technology, a product's properties and behaviour and their connections, dispositions are used. Contribution to knowledge management was made through defining the information needed for technology valuation and providing tools to gather the information in the form of a practical method. The work resulted in a six-step Technology Value Mapping (TVM) method.

The TVM method improves the reliability of technology valuation, as well as cost-efficiency, thus enabling business-friendly technology decisions. The method is based on understanding and modelling dispositions; hence, if the object or technology under consideration does not contain the needed dispositions, the method cannot be used. This thesis combined theories that are commonly used in design science with technology valuation and research into value creation and capture. According to case studies, using this interdisciplinary approach could improve organizational learning and communication when making technology decisions.

TIIVISTELMÄ

Tämän työn tarkoituksena oli kehittää ja esitellä uusi teknologian hinnoittelumenetelmä valmistavan teollisuuden tarpeisiin. Tavoitteena oli tukea uusien teknologioiden arviointia ja hinnoittelua jo konseptivaiheessa parantaen erityisesti teknologian hinnoittelun luotettavuutta ja kustannustehokkuutta. Tutkimuksessa ja menetelmän kehittämisessä käytettiin konstruktiivista lähestymistapaa ja design research methodology (DRM) – tutkimusmenetelmää. Kehitettyä teknologian hinnoittelumenetelmää arvioitiin ja kehitettiin kaivosteollisuudessa kolmen eri tapaustutkimuksen avulla.

Tämä väitöskirja kontribuoi teknologian hinnoitteluun tuomalla lisää ymmärrystä ja työkaluja mallintaa teknologian vaikutuksia tuotteen kautta. Teknologian vaikutusten ymmärtämiseen käytetään tuotteen ominaisuuksia ja käyttäytymistä sekä näiden välisiä kytköksiä, dispositioita. Kontribuutio tietämyksenhallintaan on se, että teknologian hinnoittelussa tarvittava tieto määritellään ja sen keräämiseksi tarjotaan työkaluja käytännöllisen menetelmän muodossa. Työn tuloksena syntyi kuusivaiheinen Technology Value Mapping (TVM) menetelmä.

TVM menetelmä parantaa teknologian hinnoittelun luotettavuutta sekä kustannustehokkuutta, mahdollistan näin ollen liiketoiminnallisesti kannattavien teknologiavalintojen tekemisen. Menetelmä perustuu dispositioiden ymmärtämiseen ja mallintamiseen, joten mikäli tarkasteltava kohde tai teknologia ei sisällä kyseisiä dispositioita, ei menetelmää voida käyttää. Tämä väitöskirja yhdistää suunnittelutieteissä yleisesti käytettyjä teorioita teknologian hinnoitteluun sekä arvon luomisen ja nappaamisen tutkimukseen. Tällä poikkitieteellisellä lähestymistavalla voitiin tapaustutkimusten mukaan parantaa organisaation oppimista ja kommunikaatiota teknologiapäätöksiä tehdessä.

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ABBREVIATIONS AND TERMINOLOGY

BIA	Business Impact Analysis
CSL	Company Strategic Landscape
DCF	Discounted Cash Flow
DRM	Design Research Methodology
DRP	Design Reasoning Pattern
EDR	Engineering Design Research
KM	Knowledge Management
OEM	Original Equipment Manufacturer
PC	Pragmatic Constructivism
PDD	Property-Driven Development
TTS	Theory of Technical Systems
TVM	Technology Value Mapping

Artefact	Output of transformation process.
Behaviour	Behaviours describe the product's behaviour including for example weight and price of product.
Communication	"Way to build a common, valid reality construction, based on which actors then decide to act in the way they do" (Mämmelä, Korhonen, Juuti, & Julkunen, 2019).
Disposition	"disposition is a part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas." (Olesen, 1992, p. 53) In this thesis it is applied as a link between product properties and behaviours.
Manufacturing industry	

“The branch of manufacture and trade based on the fabrication, processing, or preparation of products from raw materials and commodities.” (Standard Industrial Classification)

Operand — The subject of the transformation in transformation process.

Properties — The properties of an artefact describe the structure and shape of the system or product being designed. Properties, such as dimensions and material, can be chosen by a designer.

Strategic technology management

“Strategic management of technology is planning, organizing, leading and controlling of technological activities, interacting with company’s skills to apply knowledge, structures, resources and socio-economic environment, to contribute to formulation and execution of the company’s basic, long-term goals and objectives, and adoption of courses of action and the allocation of resources necessary for those goals.” (Sahlman & Haapasalo, 2009)

Technical system — “(together with human beings, the information and management systems, and the active environment) exert onto the operands the effects that are necessary to accomplish the desired transformation.” (Hubka & Eder, 1988, p. 58)

Technology — “Specific way of delivering an effect to an operand.” (Hubka & Eder, 1988, p. 260)

Technology valuation

Direct output of using valuation tools and methods for calculating the total value gained after the technology is implemented (Razgaitis, 2009).

Transformation process

A process in which an operand changes from an initial state to an output state.

Value — Desired behaviours of the transformation process and desired behaviours of artefact.

Value of technology	Change of desired behaviours of transformation process and desired behaviours of artefact between current situation and the situation after technology is implemented.

ORIGINAL PUBLICATIONS

Publication I	Mämmelä, J., Juuti, T., Korhonen, T., Julkunen, P., Lehtonen, T., Pakkanen, J., & Vanhatalo, M. (2018). Evaluating the value and costs of technology in the manufacturing industry. In P. Ekströmer, S. Schütte, & J. Ölvander (Eds.), DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th - 17th August 2018. Linköping.
Publication II	Mämmelä, J., Juuti, T., Julkunen, P., Lemmetty, P., & Pakkanen, J. (2018). Method for Evaluating the Value of Technology in the Manufacturing Industry. In WCEAM 2018, Stavanger, Norge.
Publication III	Mämmelä, J., Korhonen, T., Juuti, T., & Julkunen, P. (2019). Communicating design knowledge to support technology management in the manufacturing industry: an application of pragmatic constructivism. Proceeding of Pragmatic Constructivism, 9(1), 4–16.
Publication IV	Mämmelä, J., Juuti, T., & Julkunen, P. (2019). Technology Valuation Method for Supporting Knowledge Management in Technology Decisions to Gain Sustainability. Sustainability, 11(12), 3410. https://doi.org/doi.org/10.3390/su11123410
Publication V	Mämmelä, J., Juuti, T., Pakkanen, J., Korhonen, T., & Julkunen, P. (2019). Supporting technology decision-making in the manufacturing industry by improving the reliability of technology valuation (submitted).

AUTHORS' CONTRIBUTION

Publication I	I wrote the majority of the paper and was its corresponding author. The paper discussed a theoretical approach related to value of technology and the results were mainly formulated together with Tero Juuti. Conceptualization: Mämmelä, J., Juuti, T., Korhonen, T., Julkunen, P., Lehtonen, T., Pakkanen, J., and Vanhatalo, M. Methodology: Mämmelä, J. and Juuti, T. Data curation: Mämmelä, J. Writing—original draft preparation: Mämmelä, J. Writing—review and editing: Mämmelä, J. Supervision: Juuti, T.
Publication II	I wrote the majority of the paper, conducted the case study in the industry and was the corresponding author. Tero Juuti and Jarkko Pakkanen supported the execution of the case study and the defining of the scientific contribution related to this paper. Pasi Julkunen and Pauli Lemmetty made possible to conduct case study in the company. Conceptualization: Mämmelä, J., Juuti, T., and Pakkanen, J. Methodology: Mämmelä, J. and Juuti, T. Validation: Mämmelä, J. and Juuti, T. Enabling case study: Julkunen, P. and Lemmetty, P. Data curation: Mämmelä, J. Writing—original draft preparation: Mämmelä, J. Writing—review and editing: Mämmelä, J. Supervision: Juuti, T.
Publication III	Tuomas Korhonen and I wrote the majority of the paper. Tuomas focused more on the pragmatic constructivism theory and I contributed by delivering the case results related to case conducted in the product development view. Tero Juuti also contributed to the paper, mainly by defining the big picture on how product development activities and pragmatic constructivism can support one another. Conceptualization: Juuti, T., Korhonen, T. and Mämmelä, J. Methodology: Korhonen, T. and Mämmelä, J. Enabling case study: Julkunen, P.; Writing—original draft preparation: Korhonen, T. and

Mämmelä, J. Writing—review and editing: Mämmelä, J. and Korhonen, T. Visualization: Korhonen, T. Supervision: Juuti, T.

Publication IV I wrote the majority of the paper and was the corresponding author. Tero Juuti contributed to this publication by defining its scope and objective. Pasi Julkunen participated in the industry environment case studies.

Conceptualization: Mämmelä, J. and Juuti, T. Methodology: Mämmelä, J. and Juuti, T. Enabling case studies: Julkunen, P. Data curation: Mämmelä, J. Writing—original draft preparation: Mämmelä, J. and Juuti, T. Writing—review and editing: Mämmelä, J.; Visualization: Mämmelä, J. Supervision: Juuti, T.

Publication V I wrote the majority of the paper and was the corresponding author. Jarkko Pakkanen and Tuomas Korhonen wrote most of the literature review section and provided support with the layout of the paper. Tero Juuti contributed to this publication by guiding its scope and objective. Pasi Julkunen participated in industry environment case studies.

Conceptualization: Mämmelä, J., Juuti, T., Pakkanen, J. and Korhonen, T. Methodology: Mämmelä, J. and Juuti, T. Validation: Mämmelä, J. Enabling case studies: Julkunen, P. Data curation: Mämmelä, J. Writing—original draft preparation: Mämmelä, J., Korhonen, T. and Pakkanen, J. Supervision: Juuti, T.

1 INTRODUCTION

In the manufacturing industry, profitability is one of the main business priorities and technologies have a considerable influence on business success and economic growth (Boer, 1998; Xu & Wang, 2018). Adding strategically valuable resources, enhancing market power and achieving strategic renewal are reasons behind technology acquisition for companies (Graebner, Eisenhardt, & Roundy, 2010). Decisions regarding investments make the need for valuation of technology inescapable (Boer, 1998; Hunt, Thorn, Mitchell, Probert, & Phaal, 2007). Technology valuation is a major part of the technology decision-making process (Ilori & Irefin, 1997) and, therefore, the reliability of a technology valuation is crucial (Chiesa, Gilardoni, & Manzini, 2005).

The aim of this thesis is to support technology management and decision-making in the concept development phase (Ulrich & Eppinger, 2016) in three ways. First, through improving the reliability and cost-effectiveness of technology valuation (Mämmelä, Juuti, Pakkanen, Korhonen, & Julkunen, 2019). Second, through improving knowledge management (KM) by defining, acquiring and using critical knowledge to support technology management (Mämmelä, Juuti, & Julkunen, 2019). Third, through improving communication between different parties related to technology management (Mämmelä, Korhonen, et al., 2019). This is achieved by presenting a new technology valuation method: Technology Value Mapping (TVM) method. Technology management, decision-making and technology valuation are generally described in more detail in the following sections (1.1 and 1.2).

1.1 Strategic technology management and decision-making

This thesis uses the strategic technology management definition by Sahlman and Haapasalo (2009): "Strategic management of technology is planning, organizing, leading and controlling of technological activities, interacting with company's skills to apply knowledge, structures, resources and socio-economic environment, to contribute to formulation and execution of the company's basic, long-term goals and objectives, and adoption of courses of action and the allocation of resources necessary for those goals". Technology management is, therefore, a wide concept that includes not only technical aspects but also softer values, such as socio-economic and organizational learning. A generic technology management process model includes five elements: identification, selection, acquisition, exploitation and protection of technology (Gregory, 1995). This thesis focuses on supporting selection of technologies by evaluating the acquisition and exploitation potential of technology. Technology management routines, instead, can be organized into a four categories: producing scientific and technological knowledge, transforming knowledge into working artefacts, matching artefacts with user requirements and providing organizational support (Levin & Barnard, 2008). Levin and Barnard (2008) identify a total of 27 technology management routines. This thesis supports all mentioned technology management routine categories. Technology management is the hypernym, including coming concepts of this thesis.

As described by Gregory (1995), selection of technology is related to the technology management process. Selection of technology, instead, leads to the comparison and decision-making related to technologies. A general decision-making process includes five steps that could also be applied to technology decisions (Ilori & Irefin, 1997):

1. Definition of the problem;
2. Identification of the alternative;
3. Determination of the criteria that will be used to evaluate the alternatives;
4. Evaluation of the alternatives; and
5. Choosing the best alternative.

The focus of this thesis is on steps three and four, where technology valuation exist when monetary effectiveness is sought (Boer, 1998; Hunt et al., 2007). Generally, steps one and two are performed before interesting technology is selected for a valuation process. Choosing the best alternative is a task for managers and it is based on the valuation results and other company specific subjects.

The premise of this research is that technology decisions are made frequently in the concept development phase. New technologies have to be frequently evaluated against existing products in a product development context. This premise highlights the role of technology valuation cost-efficiency. If the decision-making process is frequent, then the reuse of collected information is beneficial to avoid unnecessary work. The above-mentioned technology decision-making context is described in Figure 1. The product offering plan is presented at the top of the figure, where the coming products are described. Decisions about new technologies have to be frequently made in relation to those products that are shown in the middle of the figure. At the bottom, the supporting technology valuation process is described, which focuses on steps three and four of the technology decision-making process.

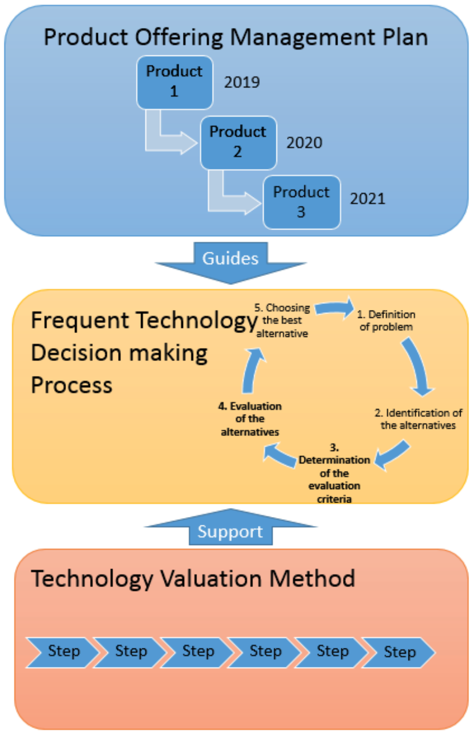

Figure 1. The technology decision-making context in concept development phase

1.2 Technology valuation and the concepts of technology and value

Technology valuation is an organization-level activity that examines the economic value of technology (see Figure 2). On the other hand, technology assessment, for example, is generally understood as an opposite concept that focuses on the country-level non-economic value. According to Razgaitis (2009), technology valuation refers to the direct output of using valuation tools and methods for calculating the total value gained after a technology is implemented. Pricing, instead, involves defining the monetary value of this technology acquisition (Razgaitis, 2009). The focus of this thesis is on technology valuation.

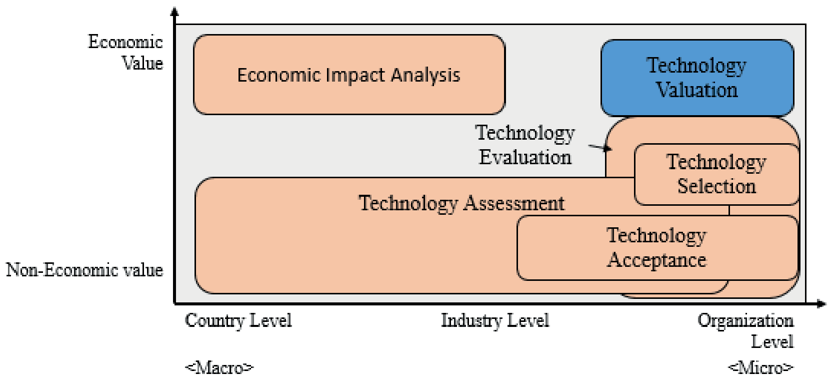

Figure 2. The technology approach context, with the main foci of this thesis marked in blue; adapted from Baek et. al. (2007)

Generally, there are three approaches for valuating an asset—cost, market and income approaches (Parr & Smith, 2005)—of which the income approach is the most frequently recommended one in technology valuation (Chiesa et al., 2005; Park & Park, 2004; Parr & Smith, 2005). The cost approach is used to evaluate the reproduction or replacement cost of technology. The main limitations of this approach are that costs do not reflect the future earning power of an asset (Chiesa et al., 2005; Jang & Lee, 2013; Park & Park, 2004; Parr & Smith, 2005) and that research and development costs can be difficult to determine (Jang & Lee, 2013; Park & Park, 2004; Parr & Smith, 2005). The market approach considers the value of an asset according to the consensus of those who have evaluated it but the data for comparison is rarely available (Jang & Lee, 2013; Park & Park, 2004). The income approach considers the future earning potential of an asset based on expected future benefits, including the discounted cash flow (DCF) calculations in practice (Park & Park, 2004). The income approach concepts includes, for example, the options methods (Yan, Hong, & Lucheng, 2010), which can be seen as more sophisticated methods in relation to the basic DCF calculations. In this thesis, the proposed TVM method (presented in Section 4) is based on the income approach according to recommendations from literature.

Although the income approach is the most frequently recommended valuation approach, it also has limitations relating to reliability and the availability of data for evaluating the future potential of technology (Chiesa et al., 2005; Jang & Lee, 2013). Its main challenges are related to the data used in a valuation process and to the assumption that the data is available and is reliable. According to Chiesa (2007): "limitation of monetary methods descends from their quantitative nature … despite the objectivity of the procedure's results, they suffer from the assumptions made during the estimation of the parameters." Dissel et al. (2009) state that prevailing quantitative valuation techniques are problematic, since DCF methods do not work well with high uncertainty and the current qualitative valuation techniques are inadequate, noting that: "few approaches exist that attempt to structure and utilize individual expert judgments and gut feel in order to improve investment decisions." Dissel et al. (2009) go on to conclude that: "further work is needed to understand how is it best to integrate the outputs into the broader technology investment processes in the firm."

This thesis and the TVM method it proposes use approaches from the sphere of engineering design research (EDR) (Andreasen, 2011; Gero, 1990; Hubka & Eder, 1988, 1996; Olesen, 1992; Weber & Deubel, 2003) to support technology management by improving the reliability and cost-effectiveness of technology valuation. Current technology valuation methods do not recognize a product at the detail level and can, thus, be thought of as "black boxes" in the technology evaluation process. Hubka and Eder define technology as a "specific way of delivering an effect to an operand" (1988, p. 260). This "specific way" is based on the assumptions outlined by Chiesa (2007), which have to be understood when sustainable technology decisions are looked at. To model the "specific way," it is essential to understand the context of technology exploitation, the business environment and the stages of the value chain investigated. To acquire the tacit knowledge by defining the "specific way," the TVM method uses a distinction between product properties and behaviour (Hubka & Eder, 1988; Weber & Deubel, 2003). The TVM method includes a description of required knowledge and of how this required knowledge can be acquired and used to support decision-making in the concept development phase.

To support decision-making, the monetary value of technology is desired. Based on the definition of technology provided by Hubka and Eder (1988), it affects produce value through an artefact (that is, a product), see section 3.4.2. However, technology can only directly affect non-monetary aspects of value. In this context, the concept of value originates from business targets and refers to non-monetary aspects, such as weight or performance, which are similar to extensive attributes (Collopy & Hollingsworth, 2009). A conversion between non-monetary and monetary value is constructed based on business contracts and is, thus, case specific. Therefore, value and technology are linked, and in this thesis, the term value refers to the ´desired behaviours of the transformation process and desired behaviours of artefact´ including both aspects of value discussed above. The value of technology is understood and evaluated according to ´change of desired behaviours of transformation process and desired behaviours of artefact between current situation and the situation after technology is implemented´.

1.3 Motivation

The motivation of this thesis originates mainly from an industry in which new technologies emerge continuously and the most promising ones have to be evaluated and selected. In practice, the challenge lies in forecasting the effects of new technologies, which is seen as a problematic task by companies within the industry. It is a technology push that guides the development and evaluation of technologies, instead of a demand-pull (Nemet, 2009). The low maturity of new technologies does not assist the technology evaluation task. A general problem in industry seems to be that efficient and reliable tools and methods do not exist and herein lies the practical motivation for this thesis. New and improved methods are also requested in existing literature, such as Dissel et al. (2009).

From an academic perspective, there are gaps related to the reliability of technology valuation. These can stem, for example, from the approaches that are generally used to research the area of value creation and technology valuation. Research in engineering design research has potential solutions to these reliability gaps and investigates the possibility of using the knowledge about product and design to support technology valuation, which further motivates the execution of this thesis.

1.4 Scientific novelty and contribution

The main contribution of this thesis is the TVM method, which improves the reliability and cost-effectiveness of technology valuation in the concept development phase. A more detailed description of the scientific novelty and contributions of this thesis are as follows, providing answers to the research questions:

- Reviewing existing technology valuation, assessment, selection and evaluation methods by focusing on the shortcomings of current methods related to the reliability of valuation results
- Proposing eight key knowledge elements that facilitate the evaluation of the effects of technology exploitation while addressing the shortcomings of current methods based on design science (answer to RQ2)
- Suggesting a novel technology valuation method, the TVM method, that considers the above-mentioned elements to support technology valuation in the concept development phase (answer to RQ3)
- Providing a practical method and tools that increase the pragmatic constructivist understanding about communication in a product development context (answer to RQ4)
- Providing a practical method and tools that focus on defining, gathering, and using knowledge to support knowledge management and permit economic sustainability in the concept development phase (answer to RQ5), and
- Improving the reliability and cost-effectiveness of technology valuation in the concept development phase (answer to RQ1)

Further details about the contribution of this thesis can be found in Section 5.2, the Conclusion.

1.5 Thesis outline

Section 1 of this thesis introduces the topic and purpose of this thesis. Section 2 describes the scientific approach employed, including objectives and the scope of this thesis. The theoretical background, focusing on the state of the art of technology valuation and engineering design research is presented in Section 3. The proposed technology valuation method is presented as the main result of this thesis in Section 4. Section 5 focuses on discussion and provides an evaluation of the relevance and validity of this research. Conclusion constitutes Section 6.

2 SCIENTIFIC APPROACH

This section describes the research design that is used in this thesis. A qualitative research design with a constructive approach is utilized due to the nature of the phenomenon investigated and the research question set. The research objective and scope is further discussed in Section 2.1, while the research methodology used is described in Section 2.2. Finally, the research questions (RQs) and the case studies used for developing the TVM method are presented in Sections 2.3 and 2.4.

2.1 Research objective and scope

The main objective of this thesis is to support technology management and decision-making in the concept development phase. It does so through improving the reliability and cost-effectiveness of technology valuation by focusing on KM and communication. The most efficient way to improve the reliability of technology valuation is to focus on the data used in valuation (Cheng, 2013; Chiesa et al., 2005; Parr & Smith, 2005). Consequently, a new technology valuation method, TVM, is presented that focuses on gathering and modelling the initial data used to conduct technology valuation and, more specifically, to visually model the assumptions made during such technology evaluation. Assumption is referred to all knowledge used to support decisions including both verified and unverified knowledge. The income approach was selected as the basis for the TVM method on recommendations from literature (Chiesa et al., 2005; Park & Park, 2004; Parr & Smith, 2005), which define what data has to be collected in order to execute valuation (Chiesa et al., 2005). A general technology valuation process consists of six steps that are described in Figure 3. Based on the shortcomings of the current technology valuation methods, the initial data used in valuation is the main foci of this thesis, shown in green colour in Figure 3.

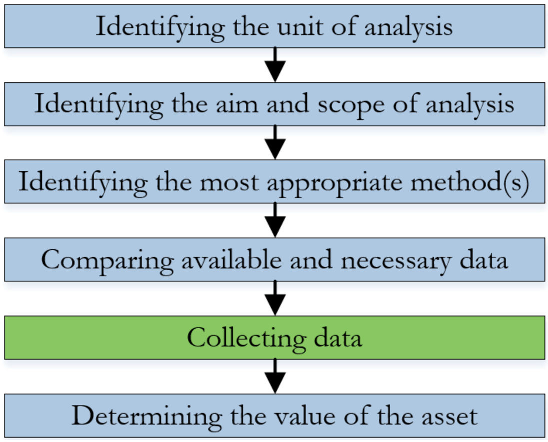

Figure 3. The technology valuation process according to Chiesa et al. (2005) and with the foci of this thesis marked in green

In this thesis, the technology acquired by a company is under analysis and the proposed technology valuation method supports the valuation from the company perspective. Technology readiness or manufacturing readiness are not in the scope of work. Risks related to acquiring and implementing the technology are not discussed in detail in this thesis. As stated above, the valuation only covers the technology potential and, therefore, the final use of the valuation results is a task for the company. The proposed method aims to be general, meaning that it could be used with different technologies and businesses.

2.2 Research methodology

The aim of this thesis is to develop and test a novel technology valuation method with scientific rigour. Hence, the TVM method is developed using design research methodology (DRM) (Blessing & Chakrabarti, 2009). An initial version of the method was derived from the state of the art of technology valuation literature and design science (Hubka & Eder, 1996). The development and evaluation of the method were conducted using three industry case studies. A global original equipment manufacturer (OEM) in the mining industry was selected to test the method. In this company, several product development and technology projects, in their early stages, were ongoing and, from these, three different projects were chosen in order to develop and evaluate the method.

The foundations of the TVM method are based on design science (Hubka & Eder, 1996). According to Blessing and Chakrabarti (2009), design research is a relatively young research field that challenges the lack of an overview of existing research, using practical results and scientific rigor:

> Design is not only a knowledge-intensive activity, but also a purposeful, social and cognitive activity undertaken in a dynamic context … Design is a complex, multifaceted phenomenon, involving: *people*, a developing *product*, a *process* involving a multitude of activities and procedures; a wide variety of *knowledge*, *tools and methods*; an *organization*; as well as *micro-economic* and *macro-economic* context. (Blessing & Chakrabarti, 2009, p. 2)

This definition of design research that is used by Blessing and Chakrabarti (2009) integrates two main strands of research—the development of understanding and the development of support. “The term support is used to cover the possible means, aids, and measures that can be used to improve design” (Blessing & Chakrabarti, 2009, p. 4). Design improvement requires: (1) a model or theory of the existing situation, (2) a vision (model or theory) of the desired situation and (3) a vision of the support that is likely to change the existing situation into the desired situation and maintain it (Blessing & Chakrabarti, 2009). The similarity of the goals of this thesis is obvious—trying to understand how technology creates value in the manufacturing industry and, based on that knowledge, how the right technology to improve products and business can be selected using the proposed method to support decision-making. The TVM method, presented in Section 4, can be understood as a design support that uses the terminology of DRM.

The method was developed using a type 3 research project (Blessing & Chakrabarti, 2009, p. 60), the components of which are presented in Figure 4. The stages of DRM are shown in the middle of the figure, the basic means of each stage are presented on the left and the main outcomes of each stage on the right side of the figure. The RQ’s are answered at the theoretical level in the research clarification (RC) and descriptive study 1 (DS-1) stages and at the practical level in the prescriptive study (PS) and descriptive study 2 (DS-2) stages. A type 3 research project can be applied for understanding the existing situation, based on RC and DS-1, and is sufficient for providing the basis for the development of the proposed method. The literature review indicates that current technology valuation methods only address part of the problem. The origin and, therefore, the reliability of the data used in technology evaluations is not fully described in the literature—

thus, new and more advanced support is needed to address this gap. A comprehensive PS is used to develop the proposed method and the initial DS-2 to evaluate it.

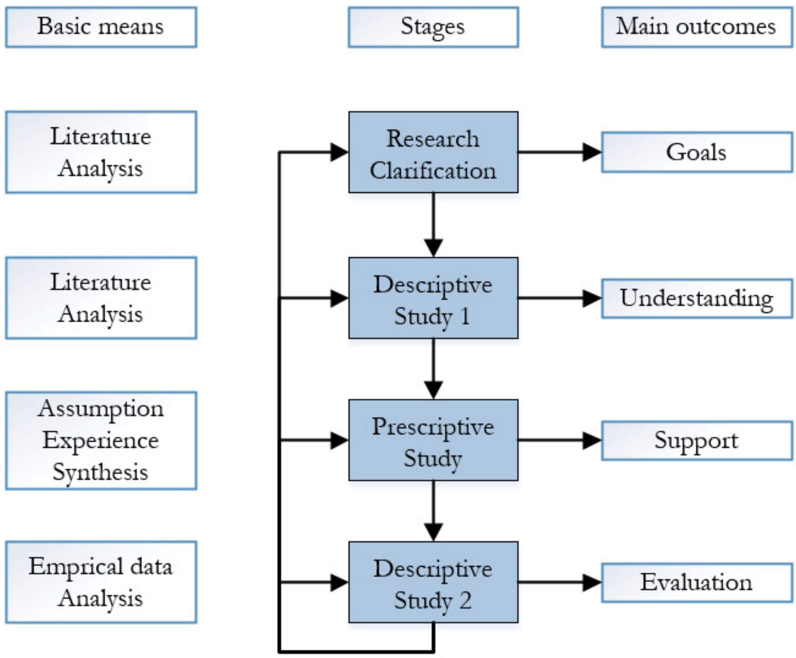

Figure 4. The DRM framework in a type 3 research project, such as the one used in this thesis (Blessing & Chakrabarti, 2009)

2.2.1 Research clarification (RC)

The first stage of DRM is the RC stage. At this stage, the goals and focus of the research are defined in order to execute it in an appropriate manner. The RC stage is based on the literature review and aims to align the stated goals with the actual focus of the research. Preliminary success criteria are also discussed at the RC stage in order to effectively evaluate the effects of the proposed method at the DS-2 stage. The deliverables at the RC stage are current understanding and expectations. DRM suggests different tools for clarifying the current state and expectations. The main portion of current understanding is presented in the initial reference model, which represents the existing design situation. Then, an initial impact model demonstrates the desired situation and shows the assumed impact of the proposed method (Blessing & Chakrabarti, 2009).

At the RC stage, the focus is placed on the literature from different fields of technology-related evaluation to obtain a comprehensive picture of it—assessment, selection, evaluation and valuation. One outcome of the RC is the revelation of an existing gap in relation to the origin of the information used for technology valuation purposes. Current methods do not describe how the information that underpins valuation (i.e. assumptions) is gathered in a reasoned and reliable manner—an initial reference model. Areas of relevance and contribution are presented in Figure 13, which is discussed in more detail in the literature review, Section 3.1.

2.2.2 Descriptive Study 1 (DS-1)

The aim of the DS-1 stage is to increase understanding of the design and its success factors by reviewing the literature. The main focus is on the explicit link between success and influencing factors. This is achieved by further identifying and clarifying the factors that influence the criteria and the way in which they do so. The outputs of the DS-1 stage are a complete reference model with success factors, measurable success factors and key factors (see Figure 9). The definitions from previous studies describe the existing situation and highlight problems—that is, the aforementioned knowledge gap. The relevance of the research topic is clarified and the main argument illustrated (Blessing & Chakrabarti, 2009).

2.2.3 Prescriptive Study (PS)

The PS stage involves developing design support, in this case the TVM method, and describing it for inclusion in the evaluation plan at the DS-2 stage (see Section 4). The understanding gathered from the previous stages is used to improve the existing situation by developing the intended support. The intended support is realized, the core concept demonstrated and the effects evaluated with the actual method, that is, with the first version of the TVM method (Blessing & Chakrabarti, 2009).

2.2.4 Descriptive study 2 (DS-2)

The DS-2 stage focuses on developing and evaluating the proposed method. An initial application evaluation is conducted that:

> Aims to identify whether the support can be used for the task for which it is intended and that it does address the factors that are directly influenced (the key factors) in the way they are supposed to be addressed, i.e., the focus is on *usability* and *applicability* (Blessing & Chakrabarti, 2009, p. 37)

Success evaluation is the second type of evaluation, which:

> Aims to identify whether the support has the expected impact i.e., whether the desired situation represented in the Impact Model has been realized, taking into account that unexpected side-effects may occur. The focus is on *usefulness*. (Blessing & Chakrabarti, 2009, p. 37)

The improvement of technology evaluation models is discussed by Noh, Seo, Sun Yoo and Lee, (2018), who consider three propositions as the criteria for improvement—coherence, appropriateness and concreteness. They remind that most previous studies focus on model development rather than on its implementation or improvement. This thesis highlights both of these views and DRM methodology in order to link the method development to its implementation and improvement. The criteria mentioned by Noh et al. (Heeyong et al., 2018) aligns with the guidelines for a DRM evaluation. The evaluation and development of the method based on DRM is described in Section 2.4, together with the introduction to the case studies.

2.3 Research questions

To develop a novel technology valuation method, the first step clarifies the gaps that exist in current methods, thus indicating where the proposed method contributes. As described in the introduction (Section 1) and the literature review (Section 3), valuations are mostly based on assumptions made during the process. Also, poor data traceability underpins the reliability challenges. Therefore, the first research question (RQ) is:

> **RQ1.** How can the reliability and cost-effectiveness of technology valuation in the concept development phase be improved?

To answer RQ1, the following four sub-questions, RQs 2–5, are answered first. Based on the literature review, the most efficient way to improve the reliability and cost-effectiveness of technology valuation is to improve the data used in the valuation. The current methods do not recognize the product and technology in detail during the valuation even the they have a significant effect on business targets (Olesen, 1992; Weber & Deubel, 2003). To understand the product role in technology valuation and in modelling the thinking that underpins assumptions, the second RQ is:

> **RQ2.** What knowledge is needed to make the underpinning assumptions visible in technology valuation in the concept development phase?

After answering RQ2, critical knowledge is defined and has to be acquired and used when the development of the method and its description is the target. The third RQ is:

> **RQ3.** How can the knowledge be acquired and used to support technology management in the concept development phase?

One perspective of method development is communication. Communication is a part of technology management (Sahlman & Haapasalo, 2009) and has an important role during knowledge acquisition and transfer in organizations. Pragmatic constructivists (PCs) (H. Nørreklit, 2017) understand communication as a way to build a common, valid reality construction, which is also the goal of the TVM method. After the method is developed, the evaluation regarding communication from the PC perspective is executed by asking the fourth RQ:

> **RQ4.** How can product development actors communicate purposefully to construct factual possibilities about new technologies?

Because technologies have a major influence on sustainability (Boer, 1998; Xu & Wang, 2018), focusing on economic sustainability especially, the KM perspective of the TVM method is evaluated by asking the fifth RQ:

> **RQ5.** How can knowledge management be supported in technology valuation to gain sustainability?

The above-mentioned research questions are primarily answered in the publications attached to this thesis, while the summary of the main findings are presented in this thesis:

- RQ1 in publication V;
- RQ2 in publication I;

- RQ3 mainly in publication II but also in publications III and IV;
- RQ4 in publication III; and
- RQ5 in publication IV.

Figure 5 summarizes the relations of DRM phases and answers the RQs. RQ2 focuses on the theoretical aspects based on the literature review, while RQ3 is answered based on practice, instead, where the first version of the TVM method is tested and evaluated. Answering RQ4 and RQ5 includes both a literature review and a practical evaluation. The answer to RQ1 is the most comprehensive one, using all DRM phases.

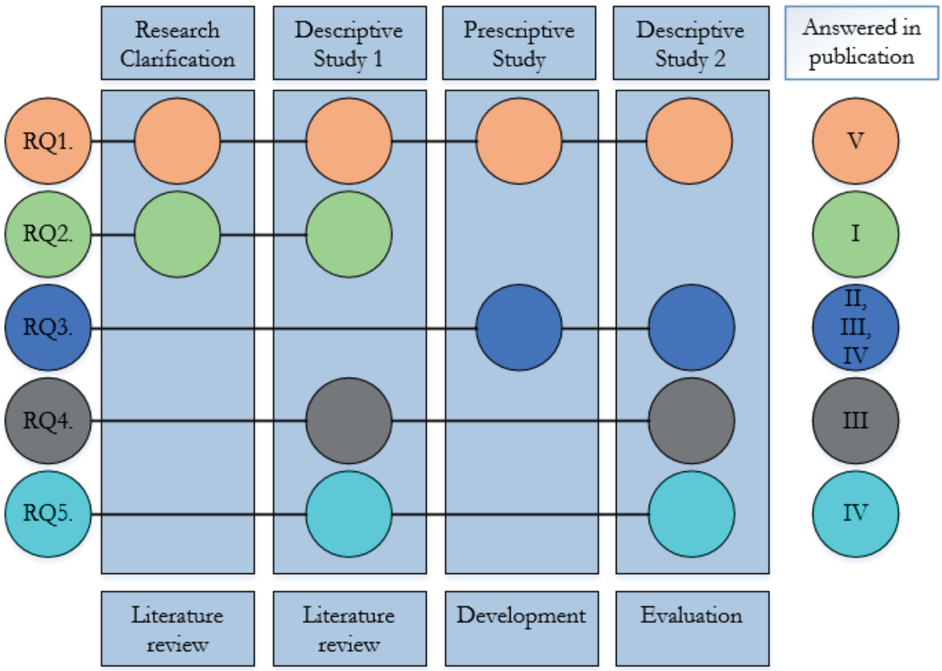

Figure 5. Research questions answered using DRM

2.4 Case studies

Three case studies, using a holistic multiple-case design (Yin, 2014) (Figure 6), are used to develop and test the TVM method. To choose a case company, three criteria are used:

1. All critical knowledge has to be available,

2. Researchers have access to data and
3. Permission to publish the results.

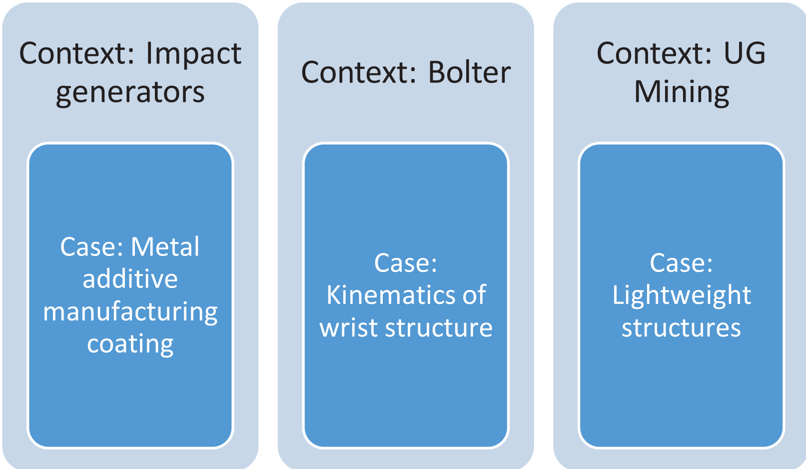

Figure 6. Holistic multiple-case design used in this thesis, adapted from Yin (2014)

In Table 1, descriptions of the case studies are shown, providing the case study name, technology used, department responsible for technology valuation, main focus of the method evaluation and development, time period and representatives of data collection as well as workload used for evaluation.

Table 1. Descriptions of the case studies used for the evaluation plan of the proposed method

No. of case study	1	2	3
Name of case study	Metal AM coating for impact generators	The kinematics of a bolter boom wrist structure	The lightweight structures of a underground (UG) boom
Technology	Metal AM coating (production technology)	Wrist structure concepts (product technology)	Lightweight solutions (low maturity idea)
Company department responsible for technology valuation	Technology Development	New Product Development	Research

Main focus of the method evaluation	Usability and applicability (DRM), identification of data sources and data validity	Usefulness (DRM); quantity and quality of data	Usefulness (DRM); sensitivity of the value indication
Data collection time period	6/2017–2/2018	4/2018–11/2018	4/2018–12/2018
Workload	98.5 work hours in 27 meetings with 7 different people	93 work hours in 15 meetings with 11 different people	56 work hours in 11 meetings with 7 different people
OEM representatives involved	Technology manager Designers (3) Manufacturing manager Manufacturing designer Technology expert (outside the organization)	Product managers (2) Design managers (3) Sourcing manager Technology manager Aftermarket specialist Designers (3)	Technology manager Product managers (2) Designers (3) Design manager

To develop and evaluate the TVM method, DRM is used with three case studies in OEM company in the mining industry, as shown in Figure 7. The initial version of the method is based on the literature review of the RC and DS-1 phases of DRM and includes four steps—in practice steps 2 to 5—presented in Section 4.2. The evaluation focus in case study 1 is on the usability and applicability of the proposed method, following measurable success factors—identification of data sources and data validity. These success factors affect the reliability of valuation result through the data collection phase of the technology valuation process, according to Chiesa et al. (2005). As presented in Mämmelä et al. (2019), the data is valid if eight key elements (Mämmelä, Juuti, Korhonen, et al., 2018) are recognized, which is the result obtained in case study 1. Two steps are added to the method based on the evaluation of identification of data sources (Mämmelä, Juuti, Pakkanen, et al., 2019) —preliminary target setting step to the first step of method and communicating the value of technology for the last step of the method.

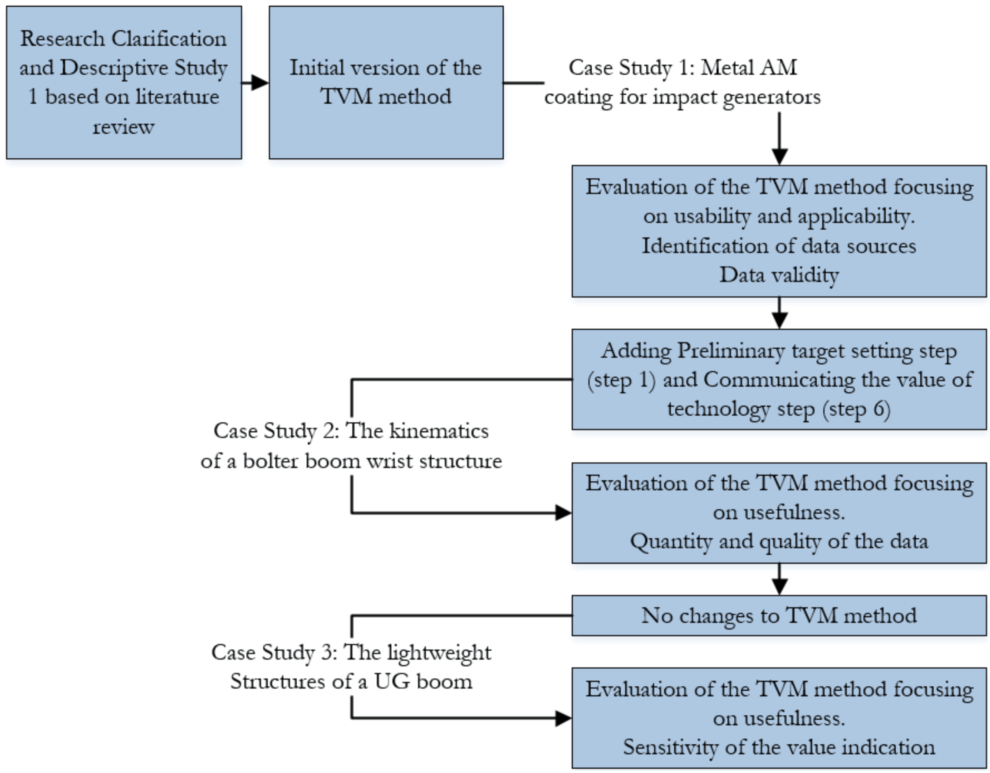

Figure 7. The process of developing and evaluating the TVM method using three case studies

Case study 2 focuses on evaluating the usefulness of the TVM method and the following measurable success factors—the quantity and quality of data (Chiesa et al., 2005; Parr & Smith, 2005). Changes made after case study 1 increase the number of participants in workshops related to case study 1, which has a positive effect on knowledge creation, especially in the target setting step. No modifications are made to the method after case study 2.

In case study 3, the sensitivity of the value indication becomes the focus, together with the usefulness of the proposed method. In this context, the sensitivity of the value indication refers to the relationships between evaluation criteria, showing what the most influential criteria are. No modifications are made to the method after case study 3.

3 THEORETICAL BACKGROUND

The purpose of this section is to discuss the shortcomings of the current technology valuation methods and how the reliability and cost-effectiveness of technology valuation can be improved according to the existing literature. Other technology approaches are also discussed, such as technology assessment and evaluation. First, the framework for investigating the phenomenon of technology valuation is discussed in general (Section 3.1), subsequent to which the shortcomings of technology valuation are described in Sections 3.2.1 and 3.2.2. The focus of the literature review is on the considerations that the authors give to the origin of the information being used and on the amount of attention they pay to the interrelation of the technology evaluation criteria. Thus, the focus is placed on how the current technology valuation methods understand the assumptions that are made during technology valuation.

Next, the approaches for modelling these assumptions are discussed. The approaches used in this thesis concentrate on building a common and valid reality construction using communication (Section 3.3.1) and on acquiring and transferring the tacit knowledge by KM (Section 3.3.2). Then, engineering design research (EDR) is proposed as a solution to modelling the assumptions and, thus, the “specific way” of technology.

3.1 Framework for investigating the technology valuation phenomenon

In this thesis the main aim is to develop a novel technology valuation method. This development focuses on supporting technology management and decision-making according to Figure 8. In decision-making, the relevance is given to the evaluation of alternatives and the determination of criterion. Contribution (yellow boxes in Figure 8), instead, is directed at KM (Alavi & Leidner, 2001; Begoña Lloria, 2008) and at value creation and capture (Lepak & Smith, 2007) of technology. Technology valuation literature is, naturally, one building block of the TVM method and this thesis contributes to technology valuation and evaluation by proposing this new method, which is based on the income approach. This research uses a constructive research approach and contributes to communication, as discussed in PC. Design science (Hubka & Eder, 1996) provides the actual tools for modelling the “specific way” of technology using the theory of technical systems (TTS) (Hubka & Eder, 1988), dispositions (Olesen, 1992) and property-driven development (PDD) (Weber & Deubel, 2003). This thesis also contributes to the TTS by highlighting the role of business contracts in guiding the targets of technology exploitation.

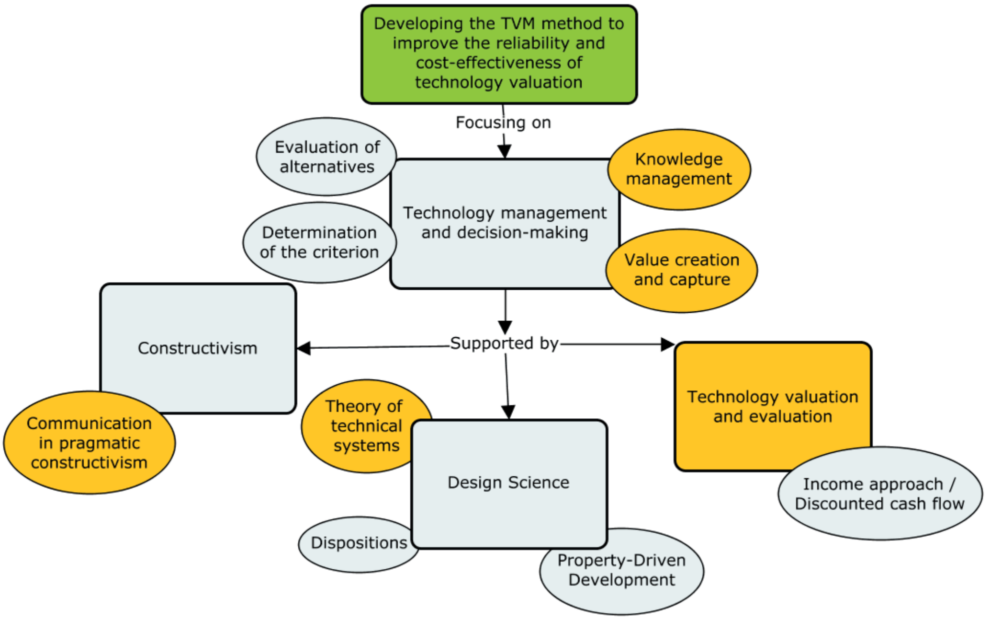

Figure 8. The framework for investigating technology valuation. Areas of relevance (all boxes) and contribution (yellow boxes) of this thesis

3.2 State of the art of technology valuation

In this section, the shortcomings of the current technology valuation and other technology approaches are discussed. Subsequently, the opportunities to improve technology valuation are reviewed in light of the literature and, finally, the contribution of technology valuation to this thesis is summarized.

3.2.1 Technology valuation

Technology influences economic benefits, such as economic growth in society and company profitability, making the valuing of technology important (Boer, 1998). Valuation of technology is inescapable because decisions regarding investments need to be made (Boer, 1998; Hunt et al., 2007). A technology asset realizes its value through its linkage to other technologies or physical assets and the valuation of those linkages is critical, according to Boer (1998). His article assumes that the insights gained from certain experts or databases can predict the probability of success as well as the probable magnitude of success versus the costs of attempting to achieve success. In addition, McGrath's (1997) paper on technology investment valuation reminds us that both cost and revenue need to be estimated.

Hitt and Brynjolfsson (1996) link the value of information technology to improved productivity, profitability and consumer value creation. They use monetary metrics to measure the value of a technology, such as return of assets and return on equity, but they do not enquire deeply into the mechanisms of actual value creation. A model for the monetary valuation of technology is proposed by Park and Park (2004). According to their model, profit-generating and cost-saving values can stem from technology (Park & Park, 2004). Importantly, their article provides no details about how knowledge for valuation is acquired (except that experts should be consulted, such as in Boer [1998] and Braun [2005]) despite this being the starting point for their model.

The paper by Baek et al. (2007) concerns technology transfer and valuation thereof. They refer to the value of technology as opportunity cost from the economic perspective. Furthermore, from the "microscopic point of view," the costs and returns related to a technology are worth estimating (Baek et al., 2007). In this case, technology value is determined by "calculating the reproduction cost of acquiring the same technology or the substitute cost of acquiring a similar asset, and then reflecting depreciation"—disregarding future benefits that might be acquired from the assessed technology (Baek et al., 2007). On the other hand, the income approach (e.g. Park & Park, (2004)) is possibly unsuited to the valuation of technologies that do not generate direct profit (Baek et al., 2007).

Baek et al. (2007) propose an integrative technology valuation model that builds on expected returns, covers market and cost structures, and considers the expected annual operating profits, the operating income, the profit generation period, the scrap value and the present value of the operating income. For a technology importer, the value of technology is determined by the expected profit, the cost of alternative technology, the internal development costs, the opportunity costs and the transfer costs (Baek et al., 2007). However, Baek et al.'s (2007) paper does not suggest how the information for the calculation of such figures should be gathered from "the subjective judgement of the developer or the owner of technology" or "patents information" (Baek et al., 2007). For instance, in that paper, the rate of the operating income is based on industrial averages, which are not very useful for the microanalysis of product or process technology investments that might replace an existing process. More precise and useful information would be valuable for understanding the operational environment and managerial work (Hall, 2010).

Chiesa et al. (2007) provide a comprehensive literature review of the technology asset value in business transactions. In their case, they are concerned about proprietary technology assets—e.g. patents and technological know-how (Chiesa et al., 2007). They make a strong point about the gathering of information for technology valuation, stating that:

> limitation of monetary methods descends from their quantitative nature, i.e. the need to translate the whole set of variables influencing the technological asset value into monetary figures; despite the objectivity of the procedure's results, they suffer from the assumptions made during the estimation of the parameters. (Chiesa et al., 2007)

Importantly, while Chiesa et al. (2007) focus on business transactions, they bring up the importance of contractual and agreement-related clauses that might have an effect on asset value—e.g. exclusivity, sub-licenses, geographic territory, remuneration form, length of the agreement, availability of technology release and restrictions.

Vega-González et. al. (2010) present a case for precompetitive technology valuation and, in their paper, technology value is determined by replacement or reproduction costs, potential value (using income methods if no price benchmark exists) and an approximation of the monetary value of intellectual property rights (Vega-González, Qureshi, Kolokoltsev, Ortega-Martínez, & Saniger Blesa, 2010). They conclude that, "Since no regulation or procedure for technology valuation exists, the decision maker's judgment is highly influential in the estimation of diverse parameters used in this valuation." Again, there is an expectation that value parameters are available.

Hartmann (2009) proposes a technology cost analysis method “to establish relations between technology values and cost values in order ultimately to be able to influence the cost level and cost structure of a product or process.” Importantly, Hartmann (2009) concludes that the costs of a technology often need to be estimated for the purpose of calculating the overall costs. As an example of estimation, Korhonen et al. (2016) provide an example of calculating technology value based on estimated cost structures—direct material cost, material overhead, direct labour cost and technology-specific labour costs.

Ultimately, it is a managerial challenge to decide what kind of valuation model to use in technology decision-making (Lingens, Winterhalter, Krieg, & Gassmann, 2016a), where the return on investment represents only an estimate of financial impact (for low impact, low uncertainty decisions). However, Lingens et al. (2016b) introduce many other methods. In their account, for decisions with high impact and low uncertainty, estimates are dependent on expert opinions.

Winter and Lasch (2016) study supplier innovation evaluation methods and state that firms use “mostly quantitative methods”—analyses of total costs, costs versus benefits and profitability. Importantly, they explicitly refer to the difficulty of data collection, for radical innovations in particular. On the other hand, with incremental innovations, historical data might be a valid reference point (Winter & Lasch, 2016).

Some authors notice a need to bring functional experts together when making technology decisions. Dissel et al. (2009) propose that a value roadmapping method could be used to build the consensus about “the future potential of new technologies” and to fuel inspiration in workshops involving commercial and technical people. Their stance is that prevailing quantitative valuation techniques are problematic, since DCF methods do not function well with high uncertainty and the current qualitative valuation techniques are inadequate, and they note that “few approaches exist that attempt to structure and utilize individual expert judgments and gut feel in order to improve investment decisions” (M. C. Dissel et al., 2009). Again, how the information needed to calculate, for example, a return on investment is gathered (with the help of commercial and technical people) remains undisclosed. In the case of technology roadmaps, Dissel et al. (2009) conclude that “further work is needed to understand how is it best to integrate the outputs into the broader technology investment processes in the firm.”

3.2.2 Other technology approaches

In this section, other technology approaches are investigated, including technology assessment, selection and evaluation. The main foci is to find out whether these approaches can provide tools for tackling the information reliability gap.

Eijndhoven (1997) explains that traditional definitions of technology assessment relate to the systematic and neutral identification, analysis and evaluation of the consequences of technology on the social, cultural, political and environmental systems and processes. Connections to private sector businesses and industry have since been made—even technology assessment has previously been connected to public decision-making and resource allocation (Tran & Daim, 2008). As an example, a model for assessing the impact of manufacturing technology on the productivity and competitiveness of a company is presented by Pretorius and Wet (2000). Their approach highlights the integration of different technologies and the relationship between a technology and a company, suggesting the technology balance sheet, income statement and technology space map analytical techniques for quantifying the impact of new technologies. Pretorius and Wet (2000) further discuss a number of evaluation criteria for replacement technologies (robotic and laser) in the manufacturing industry, such as the ability of the new technology to reduce the number of processes and the shrinkage effect on life cycles and lead times. Another example of technology assessment is provided by Yoon et al. (2018), who introduce a technology assessment model for liquefied natural gas (LNG) terminal that is based on defining key performance areas (e.g. cost structure) and key performance items (e.g. efficiency of production costs), which are empirically measurable for each area. Gartner et al. (2015) assess the technology of additive manufacturing (AM) and discuss traditional and constructive technology assessment. According to their definitions, traditional technology assessment is an analytic activity supporting decision-makers with an objective analysis of the effects of a given technology. They assert that constructive technology assessment is an interactive process that involves all stakeholders in attempting to estimate the future societal impacts of new technologies.

Technology selection is another extensive topic in technology studies. Many articles focus on the selection of manufacturing technologies. A multi-attribute decision-making model is presented by Khouja (1995), which suggests the identification of the best technology combinations for supporting vendor specifications and selecting appropriate technologies. Shehabuddeen et al. (2006)

present a technology selection framework that represents the issues surrounding the selection of manufacturing technology for practical decision-making. The authors suggest technical requirements, financial requirements and external pressures for a basic elimination of technology options. They also suggest studying the integrability, usability, supplier suitability, strategy alignment and risk as filters for the adoption of a technology. Torkkeli and Tuominen (2002) introduce a process that combines technology selection with the core competencies of a company. In their study, technology assessment is based on the information and knowledge gathered from strategic business units and expert knowledge as well as from opinions about the capabilities of each technology to fulfil the mapped selection criteria. Kengpol and Brien (2001) suggest that net present value (NPV) is a typical method for evaluating projected future cash flows and that it is important to consider this in the evaluation of technology investments. Chan, Chan, Chan and Humphreys (2006) present a list of manufacturing dimensions with specific criteria to support a technology selection process. Their approach considers both subjective and objective criteria in the selection. They focus on advanced manufacturing technologies with particular reference to computer-aided technologies. Bertoni, Bertoni and Isaksson (2018) reported a value-driven concept selection method for early system design based on a value-driven design framework (Collopy & Hollingsworth, 2009). Concepts are evaluated using weighting, input and customer oriented design analysis matrixes, which aim to link the customer value creation strategy to engineering characteristics to select the most suitable concept. This linking is done based on mathematical modelling using software that does not provide visibility to evaluate the reliability of the initial data.

Several technology evaluation studies focus on the evaluation of manufacturing technologies with reference to technology selection and comparison. For instance, Lowe et al. (2000) modify the quality function deployment (QFD) for evaluating new production technology. Importantly, they remind that this tool does not substitute valuation because of the subjectivity in weighting and interrelationships of scores. Pusavec et al. (2010) evaluate machining technologies from a sustainability perspective. Their evaluation criteria include, for example, resource energy consumption and environmental performance.

3.2.3 Opportunities to improve technology valuation

Improvement and evaluation of technology valuation methods and approaches are rarely discussed (Chiesa et al., 2005; Heeyong, Ju-Hwan, Hyoung, & Sungjoo, 2018). This may be due to the nature of technology; that is, the real benefits can only be seen after commercialization takes place, making the evaluation of the method used, therefore, difficult (Boer, 1999; Y. Park & Park, 2004; Parr & Smith, 2005). If we are unable to measure the direct effect of technology in an unequivocal manner, we are forced to use criteria that can be measured and that have a connection to the original aim (Blessing & Chakrabarti, 2009). To further understand the possible factors that are linked to the accuracy and validity of technology valuation methods, additional literature is reviewed.

Cheng (2013), Chiesa et al. (2005) and Parr and Smith (2005) discuss reliability of the technology appraisal process or, more importantly, the factors that affect the reliability, validity and precision of the appraisal results. Figure 9 presents the measurable success factors that affect the quality of technology valuation based on the findings of the three works mentioned above. The factors are identified with different colours based on the references shown in this figure. The top layer of Figure 9 presents the goals of technology valuation from company perspective. As presented by Cheng (2013), low implementation costs and ease of operation are desirable success factors for such technology valuation. Chiesa et al. (2005) add reliability, quality, validity and precision to this category. Under goals from company perspective, the steps of the technology valuation process are presented according to Chiesa et al. (2005). The bottom layer of Figure 9 shows the measurable success factors identified in the literature. These are linked to the stages of the technology valuation process. Success factors and measurable success factors are DRM concepts that are used to evaluate the proposed technology valuation method. DRM is discussed in greater detail in Section 2.2. Data validity and availability with respect to a selected technology valuation method are the most critical elements relating to valuation goals.

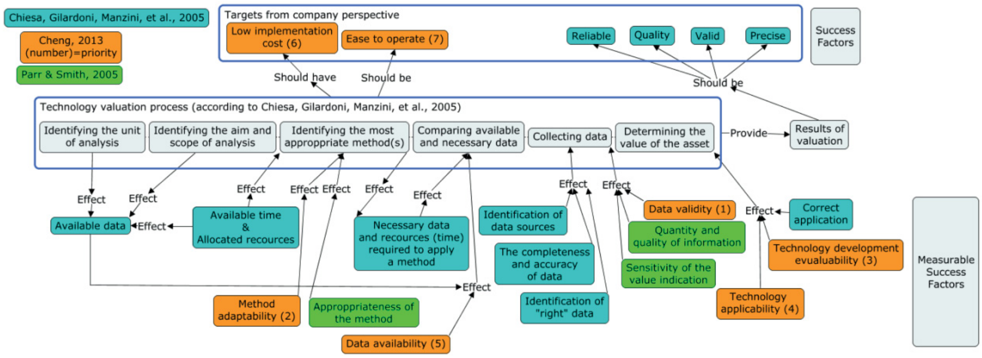

Figure 9. Measurable success factors affecting the quality of technology valuation (success factors) according to the literature (Mämmelä, Juuti, Pakkanen, et al., 2019)

This thesis focuses on the data collection phase of the technology valuation process and, more specifically, on the following four aspects from Figure 9:

1. Quantity and quality of data;
2. Sensitivity of the value indication;
3. Data validity; and
4. Identification of data sources.

3.2.4 Contribution of state of the art of technology valuation to this thesis

Based on the literature reviewed, the technology-related value considerations require the cooperation of experts from different disciplines within a company and the integration of their knowledge. It might be beneficial to consult, for example, marketing, sales, product management, engineering, production, product development, technology development and sourcing departments in order to create a comprehensive understanding of the financial and non-financial impacts of a technology decision (Laine et al. 2016a; Laine et al., 2016b). However, a gap that the prior research does not adequately cover concerns how financial impact can be derived from experts and/or databases to support real-life problem solving in the manufacturing sector. The studied articles discuss the sources of information in varying depth. Most of the approaches typically note that the source of their input information is expert opinion. Indeed, how the monetary aspects of technology decisions are determined by organizations—though important (Laine et al. 2016a; Laine et al., 2016b)—requires further inquiry in the manufacturing context. A proper methodology is needed to understand how manufacturing companies deal with variables, such as increase in total capital cost, increased output, savings in labour costs, increased maintenance costs or increased dependence on the reliability of a single machine, in their technology decisions (see Braun (2005).

Consequently, state of the art of technology valuation defines a gap for which the TVM method aims to provide improvements—making the assumptions (i.e. tacit expert knowledge) visible for understanding the “specific way” of technology. This is done by focusing on the data collection phase of the technology valuation process and improving the quality and reliability of the data used in valuation. Additionally, business contracts are take into account when monetary value is evaluated, as suggested by Chiesa et al. (2007).

3.3 Approaches for modelling assumptions

Current technology valuation methods suffer from assumptions made during the valuation process. In this section, the approaches that this thesis uses for modelling such assumptions is discussed. Technology valuation is a comprehensive task for which many participants from different functions are recommended according to the literature review. PC serves as a framework for building a common and valid reality construction between different actors through communication. KM, instead, is used to support the acquisition and transfer of tacit knowledge. Tacit knowledge, in this context, is understood as the previously mentioned assumptions.

3.3.1 Building a common and valid reality construction—Pragmatic constructivism

PC aims to answer to the problems caused by mechanical scientific thinking in management (H. Nørreklit, 2017). According to Ghoshal (2005), modern management theories are problematic to use in practice because of their philosophical underpinnings. PC focuses on the construction of valid organizational practices, aiming to develop a more productive and beneficial relationship between research and practice (H. Nørreklit, 2017). The TVM method seeks practical effectiveness and can, therefore, benefit from using the PC approach. The PC approach includes the assumption that the actors always act “under presumption of a specific actor-world relation which they continuously construct, adjust and reconstruct in light of new experiences, context and communication" (H. Nørreklit, 2017, p. 5).

An actor´s reality construction is a core PC idea, which is dimensioned by facts, possibilities, communication and values (Jakobsen, Johansson, & Nørreklit, 2011; H. Nørreklit, 2017; L. Nørreklit, Nørreklit, & Israelsen, 2006). In a technology management context, the facts are the information that is already known and the values guide the actions of people and lead to a recognition of the possibilities, which is the target of technology evaluation. Communication in PC can be understood as "a way to build a common, valid reality construction, based on which actors then decide to act in the way they do"(Mämmelä, Korhonen, et al., 2019). It is not recommended to make any decisions or actions without facts. Instead, possibilities are to be based on facts and it is beneficial to known these facts before making reasonable actions. Values act as a motivation and driving force for actors and communication is needed before real actions can be done (H. Nørreklit, 2017). Therefore, communication is one focus of this research that enables the building of the common reality construction.

Even so, communication can play an important role in management, thus it requires a more detailed description—for example, what to communicate and why. To construct a reality construction, KM is closely related to the acquisition and transfer of knowledge of both individuals and organizations. The understanding of KM in this thesis is described more thoroughly in Section 3.3.2.

3.3.2 Acquiring and transferring tacit knowledge—Knowledge management

A comprehensive review of the main approaches to KM is conducted by Lloria (2008). KM has several aspects, including:

1. It "is related both to business practice and to research." The authors researching KM come from various disciplines and provide important insights but, on their own, no individual author provides an integrating framework.

2. It "goes further than technology management or information management." Tacit knowledge, human intervention and learning are the key aspects rather than information technology.

3. It “is a broad concept, and is made up of different activities,” including, among other things, the creation and application of knowledge.
4. It “is principally found in people and is developed through learning.” Knowledge should evolve from a human asset to a business asset.
5. Developing new opportunities, creating value or obtaining competitive advantage are all possible KM aims.

Indeed, KM is a broad concept and its development has taken different directions in different countries and regions. American companies tend to be concerned with management, while European ones focus on measuring knowledge. At the same time, creating new organizational knowledge is the key for Japanese companies. The origins of these differences can stem from, for example, what the company does with the knowledge, how the knowledge is understood and who the key individuals are (Takeuchi, 2001).

KM and organizational learning research can be described as levels of KM outcomes and context (Argote, McEvily, & Reagans, 2003). The outcomes include creation, retention and transfer, while the context includes the properties of units, the relationships between units and knowledge. Choo and Neto (Choo & Neto, 2010) add an enabling condition level to the above-mentioned outcomes and context. In this thesis, the focus is placed on all three outcomes of knowledge and, at the context level, the individual and organizational knowledge is under analysis.

Earl (2001) identifies several categories and schools for the consideration of KM in order to propose a taxonomy. A systems-based technocratic school and a spatial-based behavioural school are the ones utilized in this thesis. The systems-based school aims to capture specialist knowledge and to share it for organizational use. The spatial-based school focuses, instead, on the use of space to facilitate the exchange of knowledge, which can be understood as an ideology similar to “ba” defined by Nonaka and Konno (1998). To enable reality construction between actors, individual knowledge has to be transferred to organizational knowledge. Alavi and Leidner (2001) present a model on how individual tacit knowledge can be transferred to a group´s sematic memory and vice versa. These processes can be supported by modelling knowledge and this is where the TVM method aims to provide benefit.

3.3.3 Contribution of approaches for modelling assumptions to this thesis

According to the PC presumption, facts, possibilities, values and communication are needed before reasonable actions or decisions can be made. This presumption guides the knowledge needed in technology valuation. KM supports the modelling of assumptions by providing understanding about the acquisition and transfer of tacit knowledge to organizational knowledge, which is needed in a comprehensive technology valuation (Alavi & Leidner, 2001). To acquire knowledge, the physical space is used with facilitation (Earl, Michael, 2001; Nonaka & Konno, 1998).

3.4 Modelling assumptions—Design science

As a solution for the existing gap, this section considers how product development and engineering design theories and frameworks represent technical systems and how they could support technology management. The aim is to describe generic approaches that have the potential to increase such understanding and to support the modelling of assumptions made during technology valuation in a product manufacturing context. In this context, technology is strongly connected to physical products.

3.4.1 Design science

According to Hubka and Eder (1996, p. 73), "The term Design Science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for design." Design science can be divided to four categories—design knowledge about objects, design process knowledge (design methodology), theory of design processes and theory of technical systems (TTS), where the latter focuses on technical systems (i.e. products). In this thesis, technology valuation is supported using the product and design knowledge and, therefore, TTS is described in more detail in Section 3.4.2.

3.4.2 Technology as part of a technical system—Theory of technical systems

Hubka and Eder (1988) explain that TTS focuses on describing, explaining, establishing and substantiating technical systems. The main TTS elements are presented as a transformation system that is shown in Figure 10. The need for transformation emerges when certain requirements are not met. The subject of the transformation is called an operand. The operand can be biological, energy, information or material and has both an initial state and a final output state. Transformation is needed and the process includes operations and working steps, the purpose of which is to transform the current state of the operand to a desired state. Technology is tightly related to this transformation system and can be found in transformation process at the bottom of Figure 10.

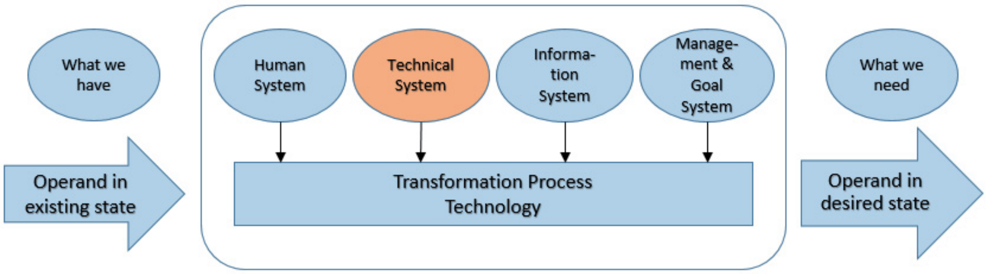

Figure 10. The transformation system, adapted from (Hubka & Eder, 1996)

Hubka and Eder’s (1988) TTS also considers the evaluation of technical systems. The authors explain that, in evaluating technical systems that perform transformations, certain properties must be selected and evaluated and a number of measures must be combined into a characteristic value that all participants understand similarly in order to answer the question: “How is the product or technology?” According to Hubka and Eder (1988), economic value is a combination of the qualities and measures of economic properties. They list examples of economic properties, including manufacturing costs, operating costs, effectiveness, prices and manufacturers.

To summarize, TTS describes the origin and the nature of technical systems, providing many generic suggestions for representing a technical system (often a product). TTS comprises a broad collection of knowledge that relates to the design of technical systems and can therefore support technology decision-making.

3.4.3 Consequences of technology decisions—Theory of disposition

Olesen (1992) asserts that the life cycle of a product should be studied when making design decisions because products may influence all systems they are a part of and phases that they undergo. Here, the concept of disposition is used. According to Olesen (1992), "disposition is a part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas." A disposition model is presented in Figure 11, showing the elements and process of the product life cycle disposition model. In this figure, we can see that an analysis-synthesis process aims to align the actual properties with goals relating to the desired artefact properties (5), by acting on artefact characteristics (2) and on artefact life-cycle characteristics (3). Dispositions (4) are the relationships between the artefact characteristics and the artefact life cycle characteristics. The artefact life cycle requirements affect the goal setting (1) or the catalyst of the model (Halonen et al., 2014).

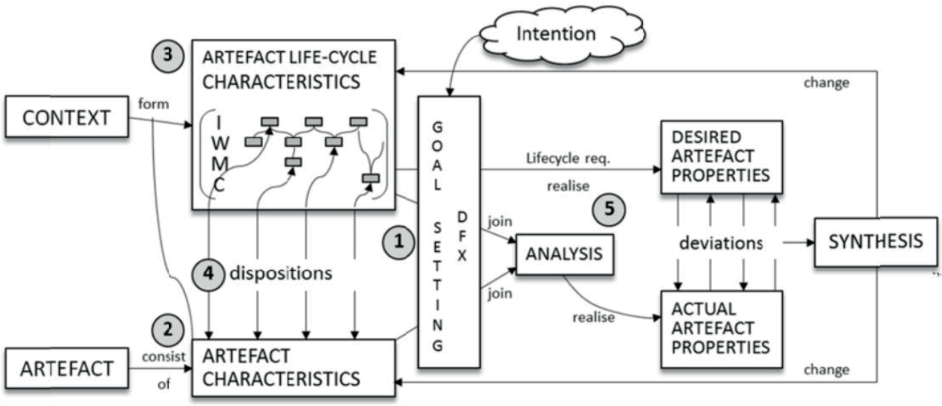

Figure 11. When decisions are made, dispositions exist (Halonen et al., 2014)

3.4.4 Expected and actual behaviour of a product—Property driven development

Products can be described in terms of several domains, such as activity, organ and part domains (Andreasen, 2011). Andreasen explains that, in each domain, it is possible to reason backwards from the desired behaviour to a structure similar to the model that Gero (1990) presents, shown in Figure 12.

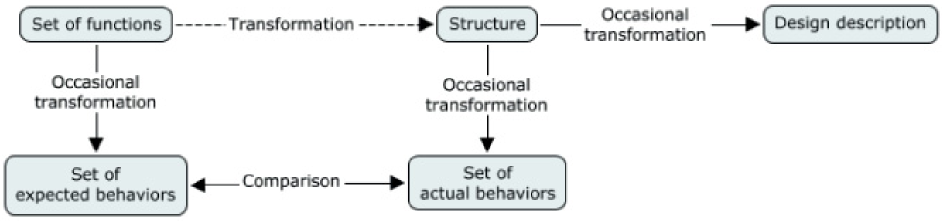

Figure 12. Function-behaviour-structure design model (Gero, 1990)

The model that is presented by Weber and Deubel (2003) in their property-driven development/design (PDD) theory has a strong similarity to Gero´s (1990) model. Differences between realized properties and design properties can be analysed using this theory. PDD considers product properties and product characteristics. Using Weber and Deubel's (2003) terminology the design parameters, i.e. characteristics, can be directly influenced by the designer. Product properties describe the product behaviour, including durability, power, speed or price of a technical system. Analysis and synthesis are two main activities in the PDD product development process. Analysis involves determining product behaviour based on known or given characteristics. Synthesis aims to assign a product's characteristics based on a given or required behaviour.

The approach by Weber and Deubel (2003) can be used to recognize the "specific way" of technology in the concept development phase and the value of technology may be evaluated according to recognized mechanisms. Using Gero's (1990) terminology, a set of expected behaviours includes the values and parameters for evaluation criteria that could be beneficial for the company. Set of actual behaviours, instead, describes the current state of a product or technology and how it fulfils the expected behaviours. In this thesis, the terms properties (causes) and behaviour (effects) are used.

3.4.5 Contribution of design science to this thesis

To support technology management, this thesis focus on recognizing, acquiring and using the tacit knowledge related to products and technologies—i.e. on modelling the assumptions. To define the knowledge needed, EDR theories is used. TTS with PDD recommends a focus on the distinction between product properties and behaviour to understand the potential effects of technology in specific contexts. These modelled dispositions are used as the primary means of communication and to form shared understanding, which is used in the TVM method. Every decision has a consequences and the dispositions are used to visualize the connections between technology decisions and their consequences.

4 TECHNOLOGY VALUE MAPPING (TVM) METHOD

In this section, the TVM method is presented as a main result of this thesis. First, an overview of the method is given in Section 4.1, followed by the steps, roles and responsibilities of the method being described in more detail in Section 4.2.

4.1 Overview

Figure 13 presents an overview of the TVM method. The steps of the TVM method are found in the middle of the figure, the tools used in workshops are found on the left and the outputs of each step on the right side of the figure. More detail descriptions about each step of the TVM method are provided in subsections 4.2.1–4.2.6. The TVM method includes six steps, from target setting to the evaluation of technical technology potential, monetary estimation and final report. Descriptions of the method using different perspectives are presented, for example, through a focus on knowledge management (Mämmelä, Juuti, & Julkunen, 2019) and communication (Mämmelä, Korhonen, et al., 2019).

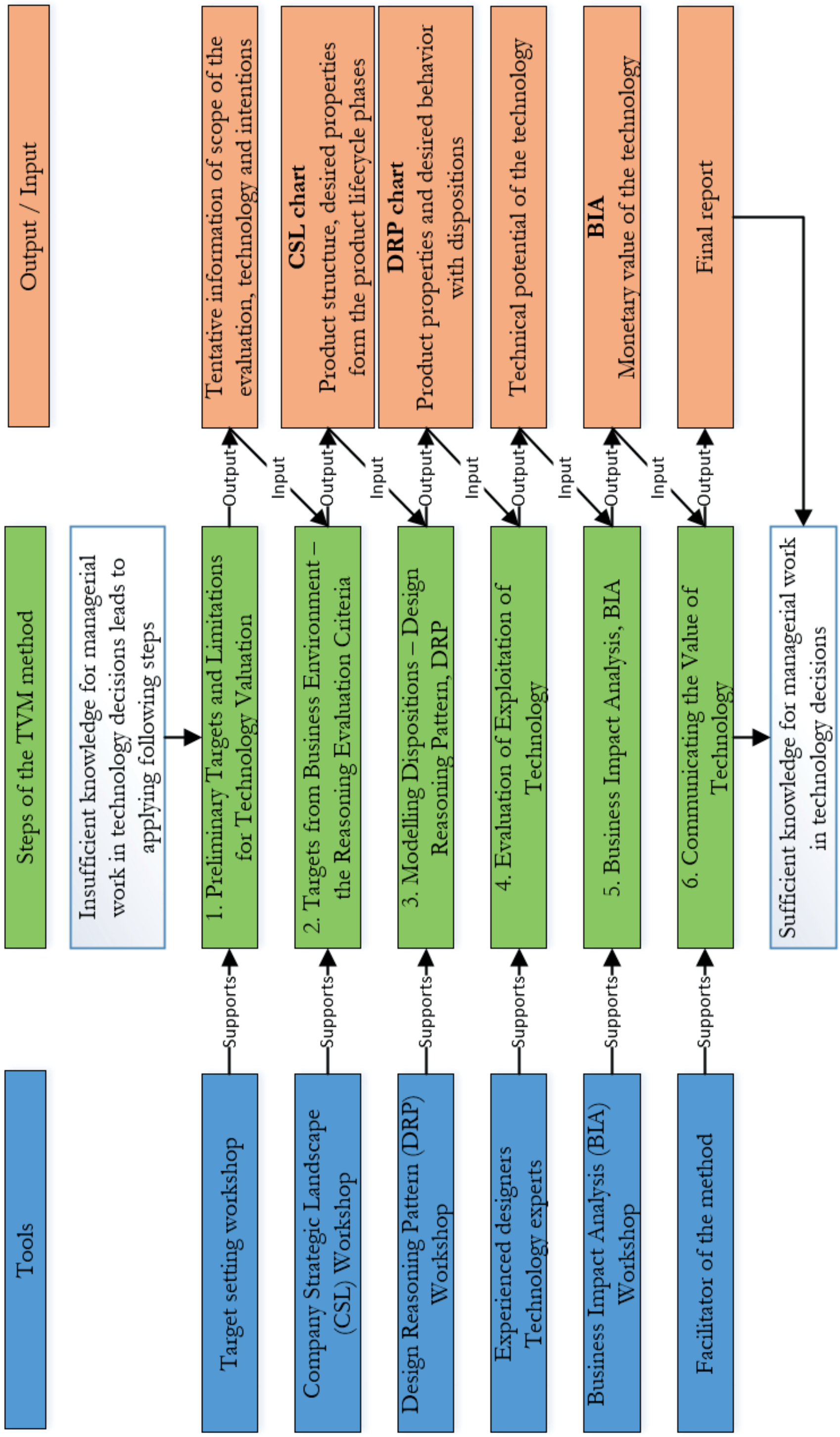

Figure 13. Overview of the TVM method

4.2 Steps, roles and responsibilities of the TVM method

In this section and its subsections, the steps and tools of the TVM method are shown. For each step, the main content is described both of verbally and using tables in which the most important aspects are highlighted. The main tools that are used are visualized in figures.

Table 2 shows the roles and responsibilities used in the TVM method through a responsibility assignment matrix (also known as the ARCI or RACI matrix), adapted from Melnic and Puju (2011). At the top of the table, the steps of the method are described and general manufacturing industry resources are shown in the left column. Letters used in the table are defined in the last row (at the bottom of the table). The role of a facilitator is to facilitate the progress of the process and to produce documentation during the process. The main authority in a technology evaluation is a product manager and technology management, while the contribution is looked all over the company organization.

Table 2. Roles and responsibilities in the TVM method

	1. Preliminary Targets and Limitations	2. Targets from Business Environment - CSL	3. Modeling Dispositions - DRP	4. Evaluation of Exploitation of Technology	5. Business Impact Analysis - BIA	6. Communicating the Value of Technology
Technology management	A/R/I	C	I	C	C	A
Product manager	A/R/I	A/R	A	A/R	A/R	A
Sales	I	C	I	C	C	I
R&D	I	C	R	R	C	I
Purchasing	I	C	I	C	C	I
Manufacturing	I	C	I	C	C	I
Site	I	C	I	C	C	I
Service	I	C	I	C	C	I
Facilitator	F	F	F	F	F	F/R

Auhority	Responsible	Contributor	Informed	Facilitator

4.2.1 Step 1: Preliminary Targets and Limitations for Technology Valuation

Main focus of step 1 of the TVM method is to set preliminary targets and limitations for technology valuation. The idea is to define and limit the scope of analysis by answering, for example, the following questions:

- Is the main purpose to improve the performance of a product or to reduce operating expenses—or both?
- What technology is being studied?
- Which organizations are being analysed?
- What products are the subjects of analysis?

This target setting workshop is guided by a facilitator and company representatives are involved. In this workshop, those responsible for technology decisions in a company should be involved in order to answer the above-mentioned questions and, thus, define the most relevant participants for step 2 of the TVM method, which sets targets from the business environment. The main content of step 1 is presented in Table 3.

Table 3. The main content of step 1—Preliminary Targets and Limitations for Technology Valuation

Why apply this step in the method?	To define and limit the scope of technology valuation.
What type of input is needed in this step?	Knowledge about the technology, products, intentions and organizations.
What are the main results of this step?	Definition of the scope of analysis.
What are these results needed for?	To select the most relevant participants for step 2.

4.2.2 Step 2: Targets from Business Environment—the Reasoning Evaluation Criteria

Step 2 of the TVM method focuses on setting targets from the business environment. This basically means defining the evaluation criteria for decision-making. The company strategic landscape (CSL) tool is used to facilitate the targets from company personnel (Juuti, Lehtonen, & Riitahuhta, 2007; Lehtonen, 2007; Pakkanen, Juuti, & Lehtonen, 2016) and it includes similar elements as the ones that Brassler & Schneider (2001) propose for the valuation of strategic production decisions. CSL includes five main elements that are relevant in the manufacturing industry—strategy, organization, processes, product and value chains (see Figure 14). Numbers in Figure 14 show the recommended order of business when a CSL workshop is facilitated. Responsibilities from all product life cycle phases are recommended in a CSL workshop to obtain comprehensive and common understanding of and agreement on targets.

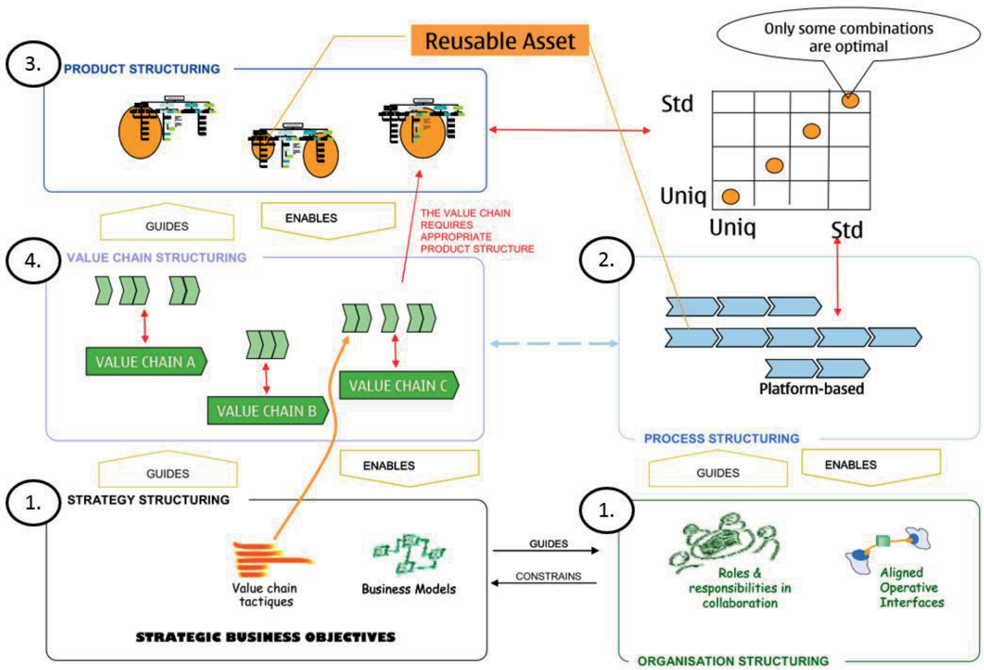

Figure 14. CSL framework, adapted from (Juuti et al., 2007)

The first phase of CSL is to define what the strategic goals are (number 1 in Figure 14), including, for example, the definition of a business model. Furthermore, the organizational structure (1) can be discussed in the beginning, which defines, for instance, the outsourced phases of processes. Process structuring in the CSL is used to describe the product life cycle phases in chronological order to understand what the desired process for the product investigated is. In the product structuring area (3), the product is divided to smaller entities to improve the technology evaluation. Logic used by designers can be set as the starting point for division, meaning that same product structuring is used that the company normally uses for design purposes. In practice, the number of elements is recommended to be between five and ten, which enables an accurate technology evaluation but does not require an unconscionable workload.

Value chains (4) are the most important area when technology valuation is goal. In this area, CLS charts the behaviours of a product that capture value. This is done during the workshop by asking participants, following the recognized order of product life cycle phases, what is valuable in each specific phase. Here the concepts of value creation and capture (Bowman & Ambrosini, 2000; Lepak, Smith, & Taylor, 2007) are used and CSL focuses specifically on understanding the behaviours that capture value. On the other hand, step 3 of the TVM method focuses on modelling the value creation. Business contracts have a major effect on these behaviours and also have to be take into account (Chiesa et al., 2007). Table 4 shows the main content of step 2 of the TVM method.

Table 4. The main content of step 2—Target setting based on the business environment

Why apply this step in the method?	To define and model the reasoning behind the business objectives relating to technology exploitation.
What approaches could facilitate technology valuation from a business perspective?	Company strategic landscape (CSL) framework.
What type of input is needed in this step?	Knowledge about the business environment of the company (strategy, processes, value chains, product structuring and organization).
How should the business objectives for technology exploitation be defined?	By focusing on elements of the business environment from the value capture viewpoint and on the relationships between the elements of the business environment.
What are the main results of this step?	Desired behaviour of the product. Product structuring for the design reasoning pattern (DRP).

What are these results needed for?	Business targets are the criteria for technology valuation.

4.2.3 Step 3: Modeling Dispositions—Design Reasoning Pattern (DRP)

Design reasoning pattern (DRP) (Juuti et al., 2014; Lehtonen, Halonen, Pakkanen, Juuti, & Huhtala, 2016) is used in step 3 to model the dispositions and describe the technology's "specific way" and, therefore, the assumptions of designers about the technology's effects. The desired behaviours and product structuring obtained from CSL is used for the base of DRP. In Figure 15, a simplified example of a DRP chart formulated during case study 1 is presented. In the middle of figure the product structure boxes (big blue outline) can be found and, on both sides of those, the behaviours that capture value (green, on the left side) and accumulate costs (nude, on the right side) are given. At the top of the figure are the ultimate targets of technology exploitation that focus on sustainability in this example. In the product structure boxes are the properties of a product that cause the desired behaviours. Arrows between different elements describe the dispositions, i.e. the assumptions, of the technology's effects.

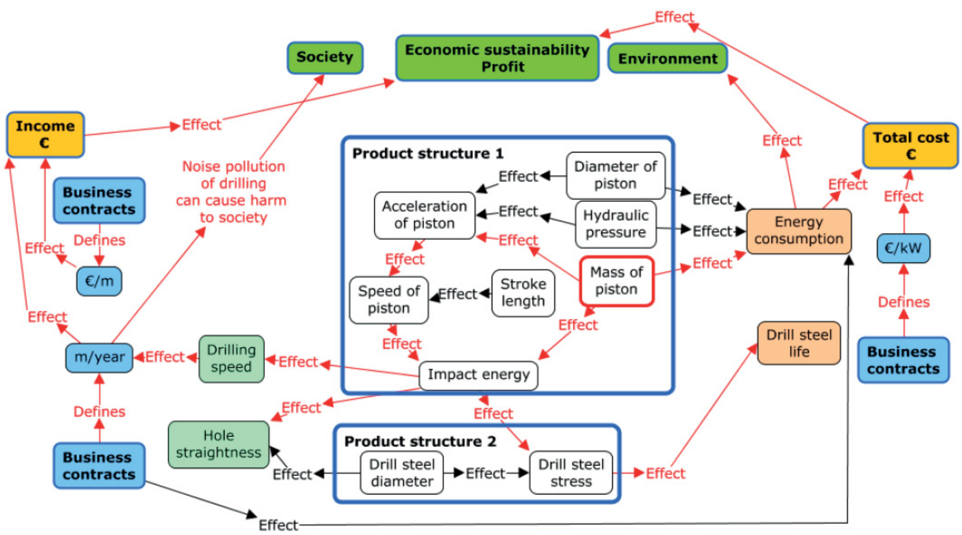

Figure 15. Example of a simplified DRP chart from case study 1 (Mämmelä, Juuti, & Julkunen, 2019)

DRP is the main tool of the TVM method for capturing individual tacit knowledge and transferring it to common organizational knowledge. Therefore, it is recommended for the most experienced designer to participate in this phase in order to have the best available design knowledge captured. Understanding modelled in DRP is used in the next step to evaluate the technical potential of a technology. The main content of step 3 of the TVM method is shown in Table 5.

Table 5. The main content of step 3—modeling dispositions

Why apply this step in the method?	To define and model the dispositions between product properties and behaviour; that is, the value capture potential.
What approaches could facilitate technology valuation from a reasoning modelling perspective?	Design Reasoning Pattern (DRP).
What type of input is needed in this step?	Targets identified from the business environment in the CSL workshop and design knowledge about the product from designers.
How to start defining the dispositions?	By focusing on targets and basic information obtained from the CLS. Relationships between the product properties and behaviour.
What are the main results of this step?	A DRP chart in which the dispositions between product properties and behaviour are shown.
What are these results needed for?	Evaluating the exploitation possibilities of a technology (step 4).

4.2.4 Step 4: Evaluation of Exploitation of Technology

Step 4 of the TVM method is focused on evaluating the technical potential of a technology's exploitation. This is done, first, with designers and, subsequently, with technology experts if they are available. The evaluation is based on the previously formulated DRP chart. The idea is to evaluate the potential of technology to change specific properties of a product. Using Figure 15 as an example and by asking: "Is it possible to affect to the mass of a piston using metal additive manufacturing technology?" If there is potential, the DRP acts as documented knowledge about how this change affects the desired behaviours that represent the evaluation criteria in a technology valuation. This evaluation is executed in facilitated workshops. The main content of step 4 of the TVM method is shown in Table 6.

Table 6. The main content of step 4—evaluation of technology exploitation

Why apply this step to the method?	Technology exploitation possibilities must be defined.
What approaches could facilitate the evaluation of technology exploitation possibilities?	Technology expert interviews and designer interviews.
What type of input is needed in this step?	Knowledge about the dispositions, from the DRP, and knowledge about the technology under consideration.
What are the main results of this step?	Potential properties on which the technology can have an effect. Numeric estimation of the technical potential of a technology.
What are these results needed for?	Potential of technology must also evaluate the monetary effect in the BIA.

4.2.5 Step 5: Business Impact Analysis (BIA)

In the business impact analysis (BIA) step, the monetary estimation of the technology explored is evaluated. To execute the evaluation, the BIA tool is used. For example, the BIA has been used when evaluating the monetary effects of product modularization projects (Pakkanen et al., 2016). An example of the BIA tool is presented in Figure 16, including the life cycle phases recognized in the CSL chart (found on the left side of the figure) and the monetary estimation criteria defined by company (found on the right side of the figure).

Valuation	One time investment	Annual investment	€	Total
Price What is the impact of new technology on the cost of the product?			-250 000 €	-250 000 €
Sales What is the impact of new technology on sales?			35 000 €	35 000 €
Project management What is the impact of new technology on product design and control?				0 €
Business contracts What is the impact of new technology on business contracts?				0 €
Transaction specific design What is the impact of new technology on transaction specific design?		-40 000 €		-40 000 €
Documentation What is the impact of new technology on documentation?				0 €
Purchase What is the impact of new technology on purchases?	800 000 €	120 000 €		920 000 €

Figure 16. Business Impact Analysis—BIA template

Based on the previous step of the TVM method, the technical potential of technology is known. In this step, the change of desired product behaviour is valuated during a BIA workshop together with all relevant life cycle phase owners. For example, if the weight of a product has increased 10 kg, according to estimation, then what effect does this have on the price of the product, sales, design and so on? Benefits are evaluated in form of maximum annual amounts using the magnitudes of the sums $1,000, $10,000 and $100,000. The main content of step 5 is presented in Table 7.

Table 7. The main content of step 5—Business impact analysis

Why apply this step of the method?	Business effects of technology exploitation must be shown monetarily to support decision-making.
What approaches could facilitate the evaluation of business impact?	Business Impact Analysis (BIA).
What type of input is needed in this step?	Detailed knowledge about the possibilities of technology exploitation and financial data.
What are the main results of this step?	Monetary estimate concerning technology exploitation.

What are these results needed in?	Decision-making, estimation of the repayment time for the new technology exploitation project.

4.2.6 Step 6: Communicating the Value of Technology

The 6th and final step of the TVM method is to communicate the value of technology for supporting technology management. Producing the final report collects the acquired knowledge into one document, which can then be distributed and used. In the TVM method, expert knowledge is gathered primarily in specific workshops in which all related participants (see Table 2) are not involved and, therefore, knowledge transfer has to be made in order to support the decision-making. The main content of step 6 is presented in Table 8.

Table 8. The main content of step 6— Communicating the value of technology

Why apply this step in the method?	To document the acquired knowledge.
What type of input is needed in this step?	All acquired knowledge during the process: description of the method steps, CSL chart, DRP chart and BIA document.
What are the main results of this step?	Final report that includes a technology feasibility study and outlines the potential of a technology in a specific business context.
What are these results needed for?	To support technology management for decision-making related to technology.

5 DISCUSSION

Here, the answers to the research questions are summarized in Section 5.1. Subsequently, the contributions to both the theoretical and practical views are discussed in Sections 5.2 and 5.3. This is followed by an evaluation of the reliability and validity of this research in Section 5.4. Finally, recommendations for future work are presented in Section 5.5.

5.1 Answers to research questions

This thesis includes a total of five RQs that are answered in five separate publications related to this thesis. RQ1 is the most comprehensive research question and, therefore, the other four RQs are answered first. RQ2 is answered in publication I (Mämmelä, Juuti, Korhonen, et al., 2018) and asks:

> **RQ2.** What knowledge is needed to make the underpinning assumptions visible in technology valuation in the concept development phase?

Publication I is based on a literature review and constitutes the base of the presented technology valuation method by focusing on the required data used for technology valuation. In this paper, the challenges of current technology valuation methods are taken into account and the reasoning behind technology decisions is highlighted through product. Eight key elements are found that must be recognized in order to evaluate the effects of technology exploitation:

- Technical system intention and business intention;
- Product life cycle phases;
- Desired behaviours from life cycle phases;
- Product structure;
- Technology characteristics;
- Dispositions between product properties and desired behaviour;

- Potential effects of the technology related to product; and
- Estimation of financial numbers related to product.

The eight key elements stated above are used in publication II (Mämmelä, Juuti, Julkunen, Lemmetty, & Pakkanen, 2018), where the first version of the TVM method is developed. RQ3, which is answered in publications II, III and IV, asks:

> **RQ3.** How can the knowledge be acquired and used to support technology management in the concept development phase?

Publication II is based on both literature and practical tests conducted in the industry through a case study. The case study relates to metal additive manufacturing coating in rock drills. The final version of the TVM method is presented in Section 4 of this publication, which includes six steps, while the first version includes only five steps. Collecting the information is primarily performed in company workshops using different tools—e.g. DRP, where design knowledge is gathered, and BIA, where the economic value of technology is estimated and documented. Eight key elements are gathered during the following steps:

1. Preliminary Targets and Limitations for Technology Valuation:
    a. Focusing on technical system intention, business intention and technology characteristics.
2. Targets from Business Environment—The Reasoning Evaluation Criteria:
    a. Focusing on product life cycle phases, desired behaviours from life cycle phases, product structure.
3. Modeling Dispositions—Design Reasoning Pattern (DRP):
    a. Focusing on dispositions between product properties and desired behaviours.
4. Evaluation of Exploitation of Technology:
    a. Focusing on the potential effects of technology related to product.
5. Business Impact Analysis (BIA):
    a. Focusing on estimating the financial numbers related to product.
6. Communicating the Value of Technology.

The TVM method is mostly based on design knowledge and could, therefore, be understood as a constructivist method. The PC (H. Nørreklit, 2017) perspective is evaluated in the technology decision-making area of publication III (Mämmelä, Korhonen, et al., 2019), where the addressed RQ asks:

> **RQ4.** How can product development actors communicate purposefully to construct factual possibilities about new technologies?

In this paper, case study 1 is used as a practical evaluation to evaluate the usability of the proposed technology valuation method. The main idea of PC is to combine the facts, possibilities, communication and values of actors in a complicated environment, like that of the manufacturing industry, and to find the tools that works in practice. The TVM method is found to be beneficial when communicating the possibilities of new technologies. The method focuses on distinction between product properties and behaviour—and, by understanding those dispositions, the communication between different parties in a company is improved.

Communication and KM are closely related to one another. Thus, the KM perspective of the TVM method is evaluated against gaining sustainability, which can be seen an important aspect of technology management. This is done by asking:

> **RQ5.** How can the knowledge management be supported in technology valuation to gain sustainability?

The TVM method supports KM by defining key individual and organizational knowledge and by providing tools to acquire and use this knowledge to gain sustainability. KM with communication supports the actors' reality construction and organizational learning, which can be used to support technology decisions.

The fifth publication (Mämmelä, Juuti, Pakkanen, et al., 2019) focuses on the reliability and cost-effectiveness of technology valuation and its RQ asks:

> **RQ1.** How can the reliability and cost-effectiveness of technology valuation in the concept development phase be improved?

The reliability of technology valuation is mostly related to the use of an appropriate technology valuation approach and reliable data, as the bases of valuation. The TVM method focuses on the reasoning behind the initial data used in a valuation and this is done by concentrating on understanding the properties of a product. Based on three case studies conducted during the research process, the TVM method is found to be able to support the reliability improvement of the data used in valuation and, therefore, the reliability of valuation results. The cost-effectiveness of technology valuation is also improved through the reuse of the information collected during a valuation process. Valuation is seen as a frequent activity and, therefore, the reuse of information is beneficial.

5.2 Contributions and theoretical implications

The main contribution of this thesis is the TVM method, which describes six steps for acquiring and using required knowledge to improve the reliability and cost-effectiveness of technology valuation in the concept development phase. A more detailed description of TVM method is provided in Section 4. The contributions of the TVM method have been evaluated against technology management, technology valuation, competitive advantage of companies, technology decision-making, pragmatic constructivism, Design Science, value creation and technological value capturing as well as technology-related knowledge management in the respective subsequent subsections 5.2.1–5.2.8.

5.2.1 The TVM method and technology management

The TVM method contributes to technology management by proposing a novel technology valuation method supporting practical decision-making challenges related to technologies in the concept development phase. The TVM method focuses on the generic technology management process (Gregory, 1995), to supporting selection of technologies by evaluating the acquisition and exploitation potential of a given technology. The TVM method also supports four technology management routine categories described by Levin and Barnard (2008): producing scientific and technological knowledge, transforming knowledge into working artefacts, matching artefacts with user requirements and providing organizational support by providing specific way to proceed and tools to gather information.

5.2.2 The TVM method and technology valuation

The TVM method contributes to technology valuation by improving the reliability and cost-effectiveness of technology valuation by visually modelling assumptions made during the valuation process, revealing the reasoning underlying technology valuation. The main contribution focuses on the data collection phase of the technology valuation process, using Chiesa et al.'s (2005) process description.

A prevailing assumption of current technology valuation methods is that the data used for valuation is available and reliable. Nevertheless, expert knowledge (Lingens et al., 2016b; McGrath, 1997) and assumptions (Chiesa et al., 2007) primarily constitute the information sources used in valuation methods. Consequently, the reliability of information and valuation results cannot be evaluated objectively. The TVM method addresses this gap by focusing on understanding and modelling the distinction between product properties and behaviour, making assumptions visible and evaluable. Based on three case studies conducted during the research process for this thesis, this approach has been beneficial in determining valuation result reliability.

The theoretical implications of this thesis consist of shifting the focus of technology valuation towards understanding a product and its design from accounting or resource perspectives. A product defines a technology's potential for value creation and capture, making understanding the product essential (Hubka & Eder, 1988; Olesen, 1992; Weber & Deubel, 2003). Using technology decision dispositions (Olesen, 1992) enables modelling and illustrates the reasoning behind technology decisions.

5.2.3 The TVM method and competitive advantage of companies

The TVM method contributes to competitive advantage of companies by improving the reliability and cost-effectiveness of technology valuation in the concept phase, enabling the selection of technologies with the greatest potential. New technologies have substantial effects on company profitability and a society's economic growth. If appropriate technologies can be selected routinely, then company level competitive advantages become achievable. The TVM method supports evaluating the effects of technologies during the concept phase, providing the potential to select the most suitable technologies for further company level development. One premise of this research was that technology decisions and valuations must be performed frequently in the concept development phase. The TVM method supports frequent valuation and decision-making processes by providing the potential to improve valuation accuracy after each valuation round, making the processes more reliable and cost-effective and thereby supporting achievable competitive advantage. (Mämmelä, Juuti, & Julkunen, 2019) discuss this subject further, using the term ‘economic sustainability’ to refer to competitive advantage.

5.2.4 The TVM method and technology decision-making

The TVM method contributes to technology decision-making (Ilori & Irefin, 1997) by supporting the phases of determination of the criteria that will be used to evaluate the alternatives and the evaluation of the alternatives. Criteria determination is formulated in a CSL workshop where business environment targets are captured with company personnel. Evaluation of the alternatives instead is mainly based on modelling the understanding of product properties and behaviours in DRP workshops and evaluating the monetary value of technology in BIA workshop. Technology decision-making principles has also been used in designing the Techne method, contributing directly to the TVM method.

5.2.5 The TVM method and pragmatic constructivism

The TVM method contributes to pragmatic constructivism by forming a causality from fact to technology possibilities using the best available knowledge of a product and its design. From a pragmatic constructivist perspective, this thesis elaborates upon communication in a product development context, thereby contributing to topical discussions on communication, which increases pragmatic constructivist understanding on communication in the following ways:

- Co-authorship can take the form of converting (human) values into technical forms, which adds to Laine et al. (2017).

- Target setting was emphasized for reality construction and knowledge integration, adding to Rantamaa et al. (2014) and Laine et al. (2016b).

- Workshop facilitators can serve as boundary subjects (corroborating and supplementing Laine et al., (2016b)) and communication hubs (resonating with Laine et al., (2017)) in a purposeful manner.

- Modelling of technical dispositions and communication among experienced designers can yield impactful communicative probes, which elaborates upon Jönsson and Johansson (2011)).

- Both top-down and bottom-up modes of communication were witnessed, elaborating upon the findings of Laine et al. (2017), and

- Communication is an important vehicle of verification, particularly by using design and technology experts opinions (resonating with Leotta et al., (2018)).

5.2.6 The TVM method and Design Science

The TVM method contributes to Design Science (Hubka & Eder, 1996), more specifically to TTS (Hubka & Eder, 1988), by proposing that business contracts, which dictate how to capture value, must be accounted for when economic design value is evaluated. Management and the goal system of a transformation system (Hubka & Eder, 1988) propose several aspects which affect design value but do not recognize business contracts. The TVM method accounts for business contracts, contributing to product development research. Capturing the value is done according to business contracts, while value creation can be understood as a means of enabling value capturing.

The TVM method also shows the need for understanding human motives (values) in given organizations to support technology decisions, which contributes to design research. In other words, the systematic use of design knowledge in constructing causality to support technology decisions forms the one research implication from an engineering point of view. Such action is performed using the approach provided by pragmatic constructivists and is described greater detail in Section 5.2.5.

The main difference between the TVM method and current technology valuation methods is the focus on product when evaluating technology potential. That being said, concepts on product properties and behaviours originate from TTS, illustrating that TTS contributes to the TVM method by forming the latter’s base.

5.2.7 The TVM method, value creation and technological value capturing

The TVM method contributes to research in the spheres of value creation and technological value capturing by examining the role of a product in this context. Research in this area originates, for example, from sociological and organizational theorists and management scholars (Lepak & Smith, 2007). Previous approaches have not recognized the product and, hence, cannot cover the subject of value creation in the manufacturing industry completely. Based on theories in the sphere of engineering design research (Hubka & Eder, 1988; Weber & Deubel, 2003), technology is affected through products and the proposed technology valuation method increases the understanding of value creation and capture phenomena by focusing on design knowledge. During the technology valuation process proposed in Section 4.2, the TVM method suggests that a distinction between product properties (creation) and behaviours (capture) can be used to increase understanding about value creation and technological value capturing in the manufacturing industry.

5.2.8 The TVM method and technology-related knowledge management

The TVM method contributes to technology-related knowledge management by defining eight key knowledge elements (answer to RQ2 in Section 5.1) and describing how this critical knowledge can be acquired (answer to RQ3), modelled (CLS, DRP and BIA tools) and used to support technology decisions. For acquiring knowledge, the TVM method uses workshops and physical spaces, as per Earl (2001) and research by Nonaka and Konno (1998). Transferring individual tacit knowledge to a group´s sematic memory is performed according to the model proposed by Alavi and Leidner (2001).

5.3 Practical implications

The main goal of this thesis is to support management in technology-related decision-making and, especially, in the technology valuation process. A technology decision affects an array of company processes—from the smallest product details to the overall company vision and strategy. Therefore, a comprehensive understanding of the effects of a technology decision has to be formulated. The TVM method presents a practical tool that can be used to support the previously mentioned subjects. It is based on a pragmatic approach in which communication between different parties plays a significant role. The method's focus on compulsory subjects is related to technology potential and guides communication towards fact based subjects instead of presumptions or preferences.

Related to the general technology management process (Gregory, 1995), the TVM method supports the evaluation of technology acquisition and exploitation potential. It further supports, through technology management routines (Levin & Barnard, 2008), the improvement of both the reliability and the cost-effectiveness of technology valuation by focusing on the data used in the valuation process in accordance with Chiesa et. al. (2005), Cheng (2013) and Parr and Smith (2005). The above-mentioned subjects also support the improvement of KM in relation to technology decision-making. By defining the required knowledge and providing tools to acquire and use it, the TVM method also supports organizational learning in accordance to Alavi and Leidner (2001).

The proposed method seeks practical results in the industry context and has a pragmatic nature. Its contribution to PC (H. Nørreklit, 2017), focusing on communication related to factual possibilities of technology, is also presented in this study. Product and design knowledge is seen as a beneficial focus when communicating between different parties in the industry context. A product has attachments to all functions within a company and, therefore, provides a natural focus area when a reliable decision is looked for.

5.4 Reliability and validity

The reliability and limitations of this research were evaluated from two perspectives. The first perspective examines the reliability of the chosen research approach. Case study research (Yin, 2014) was used and three case studies were undertaken using different business areas of the same company. Consequently, difficulties with result generalization exist from this perspective. DRM is also a qualitative research methodology and, as such, a statistical reliability evaluation of the results cannot be completed. A premise of this research was that quantitative data, such as industrial averages, is not the most reliable source of information in the manufacturing industry context, where the target setting is formulated by people in a given company. The chosen qualitative research approach decreases the probability of achieving the same results if the research is replicated.

The second perspective examines the reliability of the TVM method. Conducting three case studies also affected result generalization, although the TVM method was found to be beneficial in all three case studies. Relying on the knowledge and capability of a given facilitator and company personnel in workshops can affect the results provided by the TVM method. There is also a possibility that not all of the notable information was acquired or that the DRP model was not fully valid, leading to incorrect valuation results. Facilitated workshops can also generate misinformation related to the effects of technologies, which can strengthen incorrect understandings at both individual and organizational levels and cause harm to a company. However, compared to existing technology valuation methods, the TVM method improved the state of the art by visually modelling assumptions made during the evaluation, even though the modelling relies on previously mentioned knowledge and capability.

The capability of company personnel to reach joint understandings (such as those concerning the DRP model and dispositions) can also affect reliability of the method. Workshop discussions facilitate and adduce different views while increasing the potential of achieving joint understandings, but can also affect individual and group relationships negatively. Understanding a product's properties and behaviours to describe its dispositions is the basis of the TVM method. Therefore, if an evaluated product or technology does not have these dispositions or the required information is not available, then this method cannot be used.

The main focus of this research lies in supporting technology management in the concept development phase. According to the literature (Cheng, 2013; Chiesa et al., 2005; Parr & Smith, 2005), the reliability of technology valuation can be improved with reliable initial data. Tacit knowledge is captured, modelled and validated with company personnel in workshops—affecting the validity of the TVM method. One important aspect is that the gathered knowledge is traceable because the rationale and origin of the information is known and modelled, thus enabling an evaluation of the validity of the knowledge gained. Knowledge correction and improvement is also possible if the information is documented and commonly accepted, supporting result validity in the future. The TVM method has also seen as beneficial for communication when the factual possibilities related to technologies are evaluated using a PC approach. Product properties and behaviours are linked to all company functions, making the TVM method a communication tool that can support knowledge acquisition and sharing.

5.5 Recommendations for future research

The TVM method should be tested in different environments and with different technologies to validate and improve its usability. In its current form, the method needs a specialized facilitator. Additionally, developing the method to be easier to use and adopt in companies is an important aspect. During the case studies, the researcher noticed that this type of new thinking models can be challenging to adopt for companies. Therefore, investigating how divergent models can be adopted most efficiently into practice is also an interesting area of future research.

Business contracts play a major role in the value capture potential of a product and, hence, these contracts have an effect on design. This is also one potential future research area, examining how the business contracts can be linked to the design in the concept phase to enable economic sustainability.

6 CONCLUSION

The aim of this thesis was to support technology management in the concept development phase by developing a practical method with scientific rigour, using approaches form design science. Current tools and methods to evaluate and manage technologies are mostly based on expert knowledge and the assumption is that this tacit knowledge is available and reliable. To improve the current state in relation to technology management, the product knowledge is taken into account and made available for evaluation and management purposes. This is done by acquiring tacit individual knowledge and modelling the distinctions between product properties and behaviours, visualizing the assumptions made during technology valuation. The method was developed and evaluated using three case studies in the industry environment and design research methodology (DRM).

The result is a six-step TVM method that supports companies to achieve a competitive advantage by improving their technology management in three ways. First, it improves the reliability and cost-effectiveness of technology valuation (Mämmelä, Juuti, Pakkanen, et al., 2019). Improved valuation accuracy supports decision-making related to technology selection by defining the evaluation criteria and selecting the best alternative (Ilori & Irefin, 1997). Second, the TVM method improves technology-related knowledge management by defining critical expert knowledge, proposing tools to gather this knowledge and using it to support technology management (Mämmelä, Juuti, & Julkunen, 2019). Knowledge transfer between individuals and the organization is also taken into account by the TVM method in accordance with Alavi and Leidner (2001). Third, communication is discussed according to the PC approach (H. Nørreklit, 2017) and can be improved between different actors related to technology management using the TVM method (Mämmelä, Korhonen, et al., 2019). In this context, the communication is understood as a “way to build a common, valid reality construction, based on which actors then decide to act in the way they do” (Mämmelä, Korhonen, et al., 2019). These three aspects constitute the managerial implications of this research.

Contribution and theoretical implications of this thesis also have three main aspects. The rallying point of all contributions is a focus on product properties, behaviour and dispositions. This approach originates from design science (Hubka & Eder, 1988, 1996; Olesen, 1992; Weber & Deubel, 2003) and provides improved and more detailed explanations about how the effects of technologies can be understood, evaluated and predicted in the concept development phase. First, the contribution is improved by understanding value creation and capture of technology (Lepak & Smith, 2007; Mämmelä, Juuti, Pakkanen, et al., 2019). Research on value creation and capture originates from, for example, managerial, sociological and organizational scholars (Lepak & Smith, 2007), and these theories do not recognize the role of a product in detail. Therefore, this thesis contributes to this area by opening the product and showing the effects of technology in the form of dispositions. In technology decision-making, where the concepts of evaluation and valuation are commonly discussed, this thesis contributes by modelling and showing the dispositions that underpin technology decisions (Mämmelä, Juuti, Pakkanen, et al., 2019). Showing the reasoning supports the evaluation of a decision made and, most importantly, enables learning—thus improving future decisions. Contribution to PC is made through the advancement of PC understanding about communication in the product development context (Mämmelä, Korhonen, et al., 2019). The TVM method supports using the best available knowledge about a product and its design to form the causality—from fact to possibilities of technology.

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Evaluating the value and costs of technology in the manufacturing industry

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Abstract

This paper aims to show the shortcomings of current technology valuation methods and propose a new approach to evaluating the value and costs of technology in the manufacturing industry. It uses dispositional thinking to show the value creation mechanisms of technology, and it uses property-driven development to evaluate the possibilities of technology by examining business and product properties. From the theoretical perspective, the paper uses Design Science, which serves as the basis for understanding technical systems and design processes.

The motivation of this paper stems from practical managerial challenges in the manufacturing industry. New technologies underlie competitiveness and enable disruptive changes. However, systematic ways to evaluate the effects of technology exploitation during the whole product life cycle are scarce. Based on prior literature, an approach that focuses on income is the most recommended monetary technology valuation method. The literature does not describe how in-depth initial knowledge should be collected as a basis for valuation. In prior research, estimations tend to rely purely on the competence of experts, and the valuation of technology can be compared to the valuation of other investments. Such approaches may not take into account the longstanding and ambiguous effects of technology exploitation.

By contrast, this paper shows that a product or concept structure has to be known in sufficient detail to understand the various effects of technology selection. These effects are built upon the fact that all artificial systems that a company realizes through an order-delivery process and that a customer realizes through a technical process are laden with intentions. Such intentions dictate that technology affects a technical system but value is captured within a business system. Therefore, the links between product characteristics and intentions have to be recognized during the product life cycle—from design to manufacturing and use.

Based on the motivation above and a review of the current knowledge, the paper contributes to the literature by presenting a new early-phase technology evaluation approach based on Design Science. This approach is based on a holistic view that requires defining technology, product, and business properties. It evaluates technology properties against product and business properties. By showing the active value creation mechanisms, this approach helps to answer the question of how to use technology efficiently with specific products in a business environment. The proposed approach to evaluate the value and costs of technology supports the development of a new technology valuation method for which this paper proposes a future research agenda.

The existing business and product environment in the industry represents the target application for the approach developed in this paper. Because technology does not have intrinsic value, practitioners and academics alike should consider the specific context of technology exploitation.

Keywords: technology, technology valuation, evaluation, Design Science, Product Design

1 Introduction

New technologies play a major role in the future competitiveness capability of many companies. In the manufacturing industry, there is an ongoing need to evaluate new technologies and their potential. The challenge is to find the most suitable technologies and valuate them correctly to make the right investment decisions.

Technology valuation can be done from many perspectives and for many purposes. The basic reason for valuation is running a business. According to Parr and Smith (2005), technology-based intellectual property valuations are needed in transaction support, licensing, and intercompany transactions. Boer (1999) stated that technology valuation serves as either internal decision support or transaction support. Internal decision support can be used to judge project proposals, and transaction support can be used for the sale of an asset, negotiation of a license, or determining taxes, among others. Current technology valuation methods can be traced to the field of financial management and are based on traditional capital budgeting techniques (Dissel, Probert, & Mitchell, 2008). The school of knowledge management has also influenced the field of technology valuation (Park & Park, 2004).

Prior research has acknowledged that technology decisions are not made in isolation, separately from operations (Aubry, Hobbs, & Thuillier, 2007; Martinsuo & Killen, 2014; Meskendahl, 2010; Mäkinen, Seppänen, & Ortt, 2014). Instead, the value of technology can be realized across a broad range of products because of operational changes that stem from particular technological decisions (Korhonen, Laine, Lyly-Yrjänäinen, & Suomala, 2016; Lyly-Yrjänäinen, 2008). Moreover, technology decisions are made in an environment in which financial values concerning the overall production system can surpass technological values in particular cases (Korhonen et al., 2016; Martinsuo, Suomala, & Kanniainen, 2013).

Technology valuation is understood in this paper as evaluating the monetary sum of the maximum benefits of technology exploitation in the target company. The monetary sum of buying technology (i.e., technology pricing) is beyond the scope of this paper. Terminology is similar to Li and Chen (2006). In this article the definition of technology is according to Hubka and Eder (1988, p. 260): "Specific way of delivering an effect to an operand." The technical system and product are understood as synonyms.

The technology valuation literature is mostly linked to the topic of intellectual or immaterial property. A limited number of works have focused purely on technology valuation. Parr and Smith (2005) defined intellectual property as referring to patents, trademarks, copyrights, and trade secrets or know-how. They stated that intellectual property and intangible assets do not create value by themselves; rather, those assets are teamed with the business enterprise in which they reside or in which they will be placed for exploitation. Boer (1999) highlighted that the value of technology is situational and that "technology does not have intrinsic value" (p. 75). Valuation can be undertaken in the context of a specific business situation.

Many authors have proposed different classifications of technology valuation methods. This research used the classification by Parr and Smith (2005), who proposed three types of valuation methods: cost approach, market approach, and income approach. These three valuation methods serve as the basis for all other valuation methods and are based on the value of future benefits of asset ownership. The cost approach evaluates the sum of money required to replace the future service capability of the subject property. The market approach seeks the value through a consensus of others have judged it to be. The income-producing capability is used in the income approach to evaluate the value of an asset (Parr & Smith, 2005).

The primary valuation method for technology is the income approach (Boer, 1999; Jang & Lee, 2013; Park & Park, 2004; Parr & Smith, 2005). Technology commercialization is a complex operation, and many variables have to be considered. The income approach with the discounted cash flow method is suitable for evaluating the effects of up-front development costs, timing, and the risk of developing technology. The cost approach does not take into account the earning power of technology. Using the market approach in the case of technology is challenging, since the needed information is rarely available (Parr & Smith, 2005). In many cases, the commercial track record related to technology is missing. Therefore, customary approaches to product or business valuations do not work well in technology valuation (Razgaitis, 2009).

Technology valuation is challenging for several reasons. First, the real benefits of technology are hard to verify because of the complex environment (Park & Park, 2004). Second, valuation is a subjective activity, and value is framed in the eye of the beholder (Boer, 1999). Third, the economic value of technology is realized only after it is commercialized in the market. Few studies have highlighted the importance of combining technology and business (Park & Park, 2004; Schuh, Schubert, & Wellensiek, 2012). Boer (1998) described the pitfalls of technology valuation in the context of free cash flow methods. The basic challenge in current technology valuation methods is that the product is seen as a black box. Actual data related to the product is needed for valuation, but current methods do not define how this information should be gathered. The phases of the product life cycle are also ignored when evaluating the effects of technology exploitation.

Using the income approach to technology valuation requires financial data related to product cost, sales, and timing. In practice, data reliability is based on the assumptions and forecasts of the relevant department. The balance sheet is a collection of costs and therefore cannot take value creation into account. It is hard to understand real value creation mechanisms through backward-looking financial reviews. In addition, combining the strategic aspects of evaluation guided by financial calculations is challenging. The subjectivity of value in technology valuation is easily ignored when the focus is on financial numbers. Concentrating on the monetary aspects in an environment where the correlation of technology and commercial success does not exist can cause errors.

This study uses an approach based on Design Science to open the technical system to the technology evaluation process. According to Hubka and Eder (Hubka & Eder, 1996, p. 73), "The term Design Science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for design." The use of an approach based on Design Science stems from the assumption that a product has a significant effect on the value creation and value capture potential of the company. Porter (1985) stated that a company's external conditions define its potential. The resource-based view emphasizes the importance of a firm's personnel (Bowman & Ambrosini, 2000). Stabell and Fjelstad (1998) studied other value creation configurations to understand and analyze firm-level competitiveness.

This research focuses on evaluating the value and costs of technology from the perspective of the company exploiting the technology. We are interested in the information that supports the evaluation process. Therefore, this study aims to answer the following research question (RQ):

> RQ: What information is needed to evaluate the value and costs of technology in the manufacturing industry based on Design Science?

The goal of this research is to investigate the potential of technology in a specific environment with specific limitations given by the company and business environment. The technology transaction method is beyond the scope of this research. The presented approach to technology evaluation can be seen as an integrated approach where both quantitative and qualitative methods are utilized (Dissel et al., 2008). The results of this approach can be used as a basis for more detailed financial calculations such as NPV or Monte Carlo simulations. The approach is highly general; the type, maturity, or business area of the technology do not limit the evaluation.

In this paper, the term "value" refers to both monetary and intangible values. Valuable properties are determined by the business owner and can be converted to monetary estimations based on the best available knowledge. Costs are used to represent monetary costs using the same logic as value.

2 Research process

This study used a constructive research strategy and the Design Research method (DRM). The study is part of comprehensive research project that develops a new technology evaluation method using a Type 3 research project (see Table 1). This type is applicable when the existing design support is insufficient, as in the case of technology valuation (Blessing & Chakrabarti, 2009). The research question was answered in the research clarification and descriptive study 1 phases (Table 1). The complete method will be developed and verified with case study research in a real industry environment in the prescriptive and descriptive study 2 phases.

Table 1. Design research method phases and selected research project type.

	Research Clarification	Descriptive Study 1	Prescriptive Study	Descriptive Study 2
Research Question	x	x		
Type 3	Review based	Review based	Comprehensive	Initial

3 Building blocks from Design Science

In the introduction, we discussed the state of technology valuation approaches and methods. Considering our research question, we will also discuss the key theories in Design Science and what kind of support they can provide for technology evaluation purposes. Artificial systems originate from human needs. Therefore, value cannot be defined in a monetary way in technical systems. A company strategy is commonly related to a specific business segment and business model where the product is a key element. The approach presented in this paper supports linking the strategic aspects to technology through the product. More accurate financial data can be achieved when the product is modeled and evaluated systematically instead of using rough forecasts. Understanding the product also enables the evaluation of the effects of technology on the whole product life cycle, something that is traditionally ignored. Because the market is not stable, pure monetary estimation of benefits can lead to wrong conclusions about technology. Focusing on valuable properties compensates for the market changes.

Based on the aforementioned reasons, we focus on theories in the field of engineering to answer the research question. The Theory of Technical Systems (TTS; (Hubka & Eder, 1988) offers a comprehensive description of technical systems. The other theories presented here were developed based on TTS. Therefore we are using following theories and approach in answering the research question. Systems thinking (Arnold & Wade, 2015) provides the theoretical background for this research. TTS is based on the idea that technical systems can be understood as a specific type of system. The theory of dispositions models and explains the complex relationship between a product and the product life cycle phases. Property-Driven development provides tools for evaluating technology in uncertain circumstances without detailed knowledge.

3.1 Theory of Technical Systems

TTS is a comprehensive and unifying theory of technical systems. All types of man-made artifacts, including products and processes, can be seen as technical systems. TTS is part of Design Science, which describes the elements related to technical systems, the design process, and knowledge about them. The main reason for developing the mentioned theories is the idea that the design can be improved if knowledge of the design process and the objects of design is available (Hubka & Eder, 1988, 1996).

All technical systems are developed to satisfy human needs. TTS uses the transformation process to describe the operand's change of state to fulfill an intention. Transformation is an artificial process in which changes are achieved through natural phenomena. The theory of properties plays a major role in understanding and developing technical systems. A technical system has properties that cause different behaviors during its life phases. These relationships are also based on natural phenomena and can therefore be designed (Hubka & Eder, 1988). TTS was used to describe the origin and nature of technical systems in this paper.

3.2 Theory of dispositions

Olesen's theory of dispositions was developed with the aim of improving the concurrent development between the product and the relevant production system. According to Olesen (1992), traditional tools and methods were unable to manage the integrated development in the early 1990s when this need appeared. At the center of the theory are the relationships between the product parameters and the parameters of the systems that realize the product and that the product meets during its life. Olesen (1992) defined a disposition as "that part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas" (Olesen, 1992, p. 53).

In this research, the concept of dispositions is understood as an idea for catching and foreseeing the effects of a design decision. Technology enables new design solutions, which can be evaluated through dispositional mechanisms. In this context, dispositions are used to evaluate the effects of technology on the whole product life cycle. Dispositions can be understood as value creation mechanisms.

3.3 Property-driven development

Characteristics-properties modeling (CPM) and property-driven development/design (PDD) are frameworks for delivering explanations of phenomena in product development and design processes. The CPM/PDD framework is not a new method, but it integrates many existing approaches. CPM is the product modeling side, and product development processes are explained by PDD (Chakrabarti & Blessing, 2014).

Weber placed the distinction between product characteristics and properties at the center of the product development process. TTS is the basic theory behind the PDD method. It is possible to define relationships between characteristics and properties based on natural phenomena using synthesis and analysis tools (Weber & Deubel, 2003).

Characteristics refer to the structures, shapes, dimensions, materials, and surfaces of a product. The designer can directly influence the characteristics. Properties describe the product's behavior; the designer cannot directly influence the product behavior but can indirectly influence it by changing the product characteristics. Behaviors such as function, weight, and testability are understood as properties. The design theory and methodology has been using the duality between properties and characteristics for a long time. Author uses different terminology but the idea behind distinction align (Weber, 2012).

This research also uses terms used by Weber. The CPM/PDD approach was applied to model the relationship between product characteristics and properties. The PDD approach was used to evaluate the possible effects of technology; the driver of the process lies in the distinction between actual and wanted properties.

4 Analysis

Our aim was to understand and evaluate the value and costs of technology in the manufacturing industry. The scope of our study is limited to the manufacturing industry, where business goals strongly guide the valuable properties. Because technology itself does not have or create value, we have to understand the context and links between technology and business. This can be done through two different systems: the business system and the technical system. Technology has an effect on the technical system, but evaluation is done in the business system. Generally, the product life cycle involves many parties with their own business systems. Evaluation is done from the perspective of the company exploiting the technology. New technologies do not necessarily have any connection to any business process or value chain, as the technology may have been developed for other purposes. In the case of new technology, the following question often arises: How does the technology fit into our business and product environment? Therefore, the product and business environment should be modeled.

Figure 1 summarizes the key knowledge for evaluating the value and costs of technology, based on the selected literature. The model applies the three key theories discussed in section 3. The content of Figure 1 is explained in greater detail in Sections 4.1–4.4.

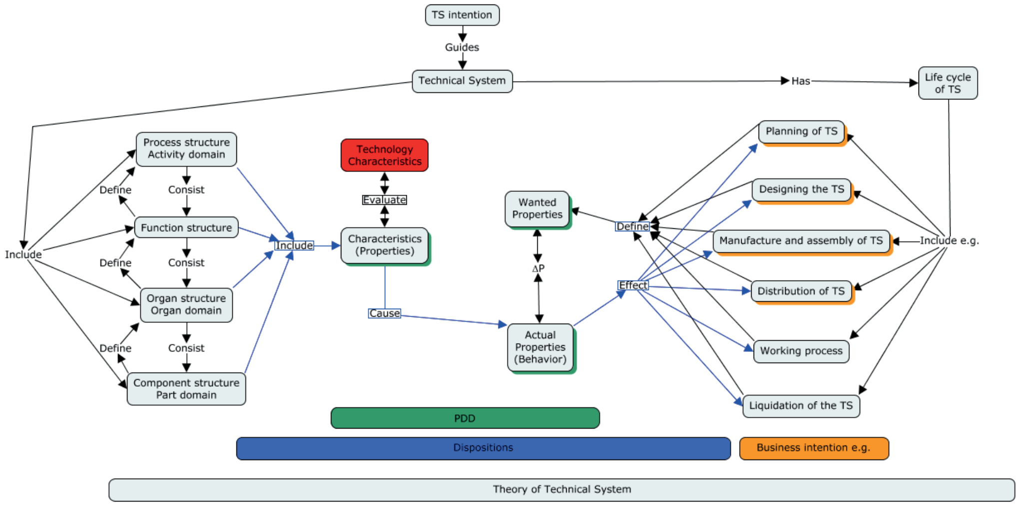

Figure 1. Knowledge required and theories used to evaluate the value and costs of technology in the manufacturing industry, based on Design Science.

4.1 Recognize intentions: Evaluation criteria

Intentions are the evaluation criteria for technology exploitation. Therefore, the definition of intentions, in both the technical system and the business system, is essential. Intentions are commonly linked to and guided by company strategy.

According to TTS (Hubka & Eder, 1988), intentions for technical systems originate from human needs. The main influencer for technical intentions is the product user, but the manufacturer also has an effect through the chosen business segment. For example, the intention of a passenger car is to transport people from place A to B. Humans also operate businesses, and business intentions are fulfilled through the technical system. The business intention for technology can be, for example, to improve profit via the performance upgrade of a product or to decrease manufacturing costs. Intention includes defining which products and business areas are at the center of analysis.

4.2 Recognize properties that create value and costs

Value and costs are mainly results of business deals and contracts. There is no exact correlation between business success and technical properties. The technical system can only produce effects such as material, energy, or information (Hubka & Eder, 1988). Therefore, wanted properties have to be defined according to the previously mentioned classes for technical systems.

TTS states that the technical system has certain life phases. A few of them, such as design and manufacturing, are common to all technical systems. Generally, every product has specific life phases, which have to be recognized for evaluation purposes.

Wanted properties for the technical system are derived from life cycle phases. Properties are results for used process in the life cycle phase. The owner of a life cycle phase has certain needs related to the product. Those needs can be business oriented or softer values. Recognizing those needs and transforming them into measurable properties for technology evaluation is the key to business-oriented technology evaluation. Wanted properties are the target values for the technical system—that is, value capture potential takes place at this point.

4.3 Model dispositions between product characteristics and properties

Technology can make a small modification to a complete product or a significant change to a product function principle. All product characteristics are derived from a product's structure. To understand the product characteristics, it is necessary to recognize the product structure. To support the modeling of product characteristics and properties, we must first define technology characteristics.

New technology is often only an idea or has low maturity when detailed specifications are not available. New product development faces the same challenges. The PDD (Weber & Deubel, 2003) approach supports the evaluation of uncertain solutions. It does not need to know all the details to predict the effects of certain characteristics.

The previous section defined wanted properties. Weber's CPM/PDD approach can visualize the connection between product characteristics and properties. Because of the countless number of characteristics and links, it is not efficient to try modeling all the product characteristics. The target of evaluation is the specific technology that guides the modeling of the product. Links between product characteristics and properties are artificial phenomena. Mentioned connections are also known as dispositions in this paper.

4.4 Evaluate the potential effects of technology

Based on the information from the previous sections, it is possible to evaluate the value and costs of technology in the manufacturing industry. The complete chain of effects from design solution to business criteria is realized. Comparing the characteristics of the technology and the product reveals the potential of specific technology by showing the active value creation mechanisms.

Evaluating the possible change of wanted properties is the key to this approach. We can evaluate and understand what are the potential characteristics where the technology has effect. Following the value creation mechanisms through product characteristics to wanted properties it is possible to evaluate the change of properties that creates value or costs. Based on best available knowledge the change of wanted properties is converted to monetary estimations. To calculate the monetary sum of effects, the real numbers or estimations of volumes, prices, and costs are needed.

5 Results

In this paper, we introduced a new approach to evaluating the value and costs of technology in the manufacturing industry based on Design Science. Main implication of this approach is opening the product and product life cycle phases to the technology evaluation process. The impacts of technology exploitation are evaluated according to recognized value creation mechanisms.

We found eight key elements that must be recognized to evaluate the effects of technology exploitation:

- Technical system intention and business intention
- Product life cycle phases
- Wanted properties from life cycle phases
- Product structure
- Technology characteristics
- Dispositions between product characteristics and wanted properties
- Potential effect of technology related to the product
- Estimation of financial numbers related to the product

This research originates from industry and introduces an approach to support decision making in technology evaluation and investment. An understanding of the dispositions and wanted properties of business supports the identification of suitable technologies in general. Utilizing this approach requires sufficient information on the product and product life cycle. The target group is the existing product and business environment.

6 Discussion

Novelty of this research is opening the product to technology evaluation process and showing the value creation mechanisms of technology. Understanding the product characteristics supports the recognition of the value creation mechanisms of technology, which have not been sufficiently examined in the literature.

Technology choices in the business environment are complex decisions. The approach presented in this paper is based on a literature review in the field of technology valuation and Design Science. The main goal was to support and improve decision making related to technological subjects at the managerial level. Based on the knowledge needed in technology evaluation, the target of technology exploitation is defined and its potential is evaluated through active value creation mechanisms. The selected theories and research method helped in answering the research question and provided a better understanding of the effects of technology in the manufacturing industry. The results are valid mainly at the theoretical level because the research is based on a literature review. Therefore, future research can investigate how this approach works in practice and how the information is gathered in the real industry environment. The approach presented here can be developed toward a new technology valuation method.

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PUBLICATION
II

Method for Evaluating the Value of Technology in the Manufacturing Industry

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Method for Evaluating the Value of Technology in the Manufacturing Industry

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Abstract The aim of this research is to develop and test a new method for evaluating the value and costs of technology in the manufacturing industry based on Design Science. The overall purpose is to enable the evaluation of product lifetime value creation already in the concept phase. This would improve the manufacturer's capability to design for the total cost of ownership and thus, improve planning in the engineering asset management context. A constructive research strategy is used, and the Design Research Method with an industry case study is applied in developing and evaluating the method. This paper contributes to the literature by presenting a new method for evaluating technology based on Design Science. Product characteristics and properties are modeled, and the technology characteristics are evaluated against them. The proposed method opens the product, which is traditionally seen as a black box in techniques for valuing technologies, to the technology evaluation process. The target application for the proposed method is the existing product and business environment where sufficient design knowledge

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is available. This method supports decision making in technology-related questions at the managerial level. This paper recognizes and uses value creation mechanisms to evaluate the value and costs of technology.

1 Introduction

Selecting a technology in the manufacturing industry can be complex because technology does not have intrinsic value. The value of a technology is realized only after it is commercialized. Developing a new technology is an uncertain process, and choices can have far-reaching effects. The overall purpose is to enable the evaluation of product lifetime value creation already in the concept phase. This would improve the manufacturer's capability to design for the total cost of ownership and thus, improve planning in the engineering asset management context (Amadi-Echendu et al., 2010). The focus of this paper is to develop and test a method that supports early phase decision making for technologies by evaluating the monetary effects of technology in the context of the manufacturing industry. The method is directed to take into account the value of the technology in the whole product life cycle. Motivation for this research came from industry where new technologies are seen as an important source of competitiveness. The target application for the proposed method is the existing product and business environment where sufficient design knowledge is available. Results of the valuation are given in monetary terms.

Traditionally, methods for valuing technology originate in financial management and are based on capital budgeting techniques. Understanding and estimating new technologies is challenging with pure monetary-based analysis and backward-looking financial reviews. Technology affects the product, and therefore, understanding the value creation mechanisms through the product is seen as beneficial. Financial estimations of traditional methods for valuing technology are mostly based on scarce forecasts where the link between the real effect of the technology and the product is invisible. Therefore, this paper contributes to current knowledge by presenting a method based on Design Science where the focus is shifted from financial data to the product.

We developed this method for technology evaluation purposes and are interested in how to gather and organize the knowledge needed in the context of manufacturing industry. Our previous study (Mämmelä et al., 2018) showed the information needed in the technology valuation context, and in this paper, we construct and develop a method based on the information. Therefore, this paper includes the following research question (RQ): How to create and structure the information to evaluate the value and costs of technology in the manufacturing industry? A constructive research strategy is used in this paper. The method is developed and tested using Design Research Method (Blessing & Chakrabarti, 2009) with case study research (Yin, 2014) in a real industry environment. The method is developed using a type 3 research project (Blessing & Chakrabarti, 2009, p. 18), which includes four main phases: research clarification, descriptive study 1, prescriptive study and descriptive study 2. The first two phases are based on a literature review, and the last two are focused on developing and testing the method which is the main focus of this paper.

Because the value of technology is situational, company-specific knowledge is the center of the analysis. The proposed method is a five-step method, and the information is gathered mainly in workshops with company and technology experts. During the process, the main targets and limitations for technology exploitation are defined. The product characteristics and properties are modeled, and the technology characteristics are evaluated against them. The technology business impact is evaluated based on modeled value creation mechanisms and available financial data. In this paper, the value is defined as follows (Mämmelä et al., 2018): “the term “value” refers to both monetary and intangible values. Valuable properties are determined by the business owner and can be converted to monetary estimations based on the best available knowledge. Costs are used to represent monetary costs using the same logic as value.”

2 Literature Review and Theoretical Foundation

This research is mainly based on ideas of Design Science. According to Hubka and Eder (1996, p. 73), “The term Design Science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for design.” The Theory of Technical Systems describes the purpose and nature of technical systems, and this theory is a major part of Design Science (Hubka & Eder, 1988). The theory of dispositions is used to catch and foresee the effects of technology exploitation decisions (Olesen, 1992). Olesen (1992) defined a disposition as “that part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas” (p. 53). Product and business modeling is done and structured according to Property-Driven Development (PDD) approach, which originates in explaining the design phenomenon and improving the design (Weber & Deubel, 2003). PDD is described in more detail in subsection 3.3.

Technology valuation can be done for many purposes and from many perspectives. The three basic valuation approaches are the cost, market and income approaches (Parr & Smith, 2005). The cost approach is based on the idea that the value of technology can be compared to the replacement cost of the technology. The market approach seeks the value of the technology based on others’ consensus. The income approach looks at the future earning power of the technology. All other valuation methods are based on these approaches. The income approach is the most recommended valuation method for technology valuation, and this paper develops a method based on the income approach (Jang & Lee, 2013) (Park & Park, 2004). One general challenge in technology valuation is that the value is framed in the eye of the beholder (Boer, 1999). As the real benefits of the technology are realized only after commercialization, only a few studies have combined technology and business (Park & Park, 2004; Schuh, Schubert, & Wellensiek, 2012). There are also approaches based on wider perspective of technologies and innovation, for example (Fox, 2013), but the general challenge of understanding the real effect of the technology remains.

The knowledge needed to evaluate the value and costs of technology in manufacturing starts from defining the technical system intention and the business intention. This determination is done in the first phase of the proposed method. To understand the wanted properties of the product, it is essential to know the product life cycle phases, which are the target of phase 2. The product structure defines the characteristics of the product. The product structure is modeled in phase 3 using Design Reasoning Pattern tool. The main idea is to find similarities between product and technology characteristics and understand the value creation mechanisms between them, phase 4. Combining the financial data in recognized technology effects, it is possible to evaluate the monetary benefit of the technology; this evaluation is done in phase 5 (Mämmelä et al., 2018).

3 Method for Evaluating the Technology

The proposed method is targeted to evaluating the value and costs of the technology in the existing business and product environment. Therefore, we can assume that the product and the business are accepted by the market at a certain level, and information related to the technology exploitation environment is available by company. The results of the evaluation support decision making in technology-related questions. In this paper, the method is understood as described by Newell (1983) by using four statements: 1. A specific way to proceed, 2. A rational way to proceed, 3. involves subgoals and subplans and 4. The occurrence is observable. The proposed method has five main phases, discussed in subsections 3.1 through 3.5. The method is created to gather the information from the targets for exploitation possibilities. The first two phases focus on target setting, phases 3 and 4 on modeling and recognizing the value creation mechanisms, and the final phase is for monetary estimation of the technology effects.

3.1 Preliminary Targets and Limitations of the Evaluation

To understand the scope of plans for exploiting the technology, the first phase defines the preliminary targets and limitations of the evaluation. Questions to answer include the following:

- Is the main purpose to improve the performance of the product or reduce the operating expenses; that is, what is the business intention?
- Which products are the target of analysis, and what is the technical system intention?
- What is the technology, and what are the characteristics of the technology?
- Which organizations are being analyzed?
- What are the development areas, and what information is static?

Information is gathered in workshops with management in relevant areas. After phase 1, tentative information about the technology and the scope of the evaluation is known. This information supports execution of the next phase and participant selection.

3.2 Targets from Business Environment

The second phase of the method is to set targets for exploiting the technology based on the business environment. The technology influences the technical system, but the effects are evaluated in the business system. Relations between the business environment and the technical system should be set as the center of analysis. Juuti *et al.* (2007) presented Company Strategic Landscape (CSL) framework which defines the elements related to the product development operations and the production of the company. The CSL framework is used to collect the product development and technology targets from the business environment.

The CSL framework includes five main areas related to a company's business environment: strategy, process, product, value chain and organization. To get comprehensive knowledge, the CSL framework is reviewed in a workshop with the management of all relevant departments defined in phase 1. The leader of the technology evaluation process should act as a facilitator in the workshop. The main outcome of this phase is a list of desired properties; see the explanation in subsection 3.3, for the technical system from the life cycle phases. The recognized properties act as the target values for the value creation mechanisms in phase 3.

3.3 Modeling Value Creation Mechanisms

The originality of this paper is to show and explain the value creation mechanisms of technology in the context of the manufacturing industry. Therefore, this phase is one of the most critical steps of the proposed method. The value and costs of technology are evaluated according to recognized value creation mechanisms. Modeling is executed based on the same principles that Property-Driven Development presents (Weber & Deubel, 2003). The concept is based on the distinction between product characteristics and properties. Characteristics are design parameters over which the designer has direct influence. Properties are understood as a behavioral aspect, such as the power or the price of a technical system. Properties are the results of characteristics and can be designed.

A Design Reasoning Pattern (DRP) is focused on modeling relations between product structuring and the value chain defined in the CSL framework. A DRP is a chart where the value creation mechanisms between the product characteristics and the business goals are recognized and presented. The CSL framework acts as the source of input in this phase, and product structuring is selected as the starting point of the DRP. Value capture and cost properties are set as the goals for the DRP. The DRP also needs input from the company's product development department. The most experienced designers should be involved in this phase. Modeling uses pull control principles to value capture and cost properties toward product structuring. In the product structuring elements are the parts and characteristics where modeling ends. The technology's characteristics should be observed and used to guide modeling the DRP for efficient results.

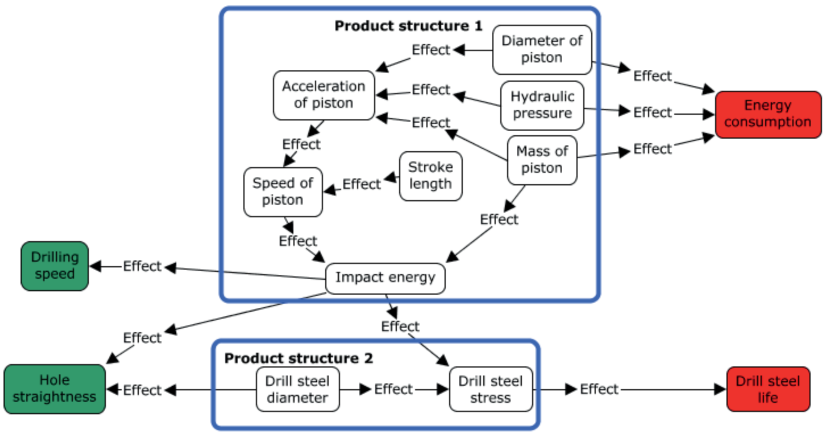

Figure 1 Example of a simplified DRP chart.

Figure 1 represents an example of a simplified DRP chart from the case study. On the left (green boxes) are value creation and the right cost (red boxes) properties recognized in phase 2. The big blue boxes in the middle are product structures. Inside the product structure is the characteristics of the technical system. Arrows describe the relations between the characteristics and properties. Relations between product characteristics and properties can be complex, and all characteristics are not equal. Generally, a few main characteristics have to be understood and controlled for an efficient design solution. There are also links between product structures.

3.4 Evaluation of Exploitation of the Technology

Evaluation of the technical potential of the technology in a defined scope and business environment is done in phase 4. Basic information is structured in previous phases, and we have recognized value creation mechanisms in the DRP. Comparing the characteristics of the technology and product from the DRP reveals the potential of the technology. The effects of the detected similarity can be evaluated based on the DRP chart. For example, the case presented in this paper was focused on metal coating with additive manufacturing. The characteristics of the additive manufacturing (AM) coating technology are related to the surfaces of the parts: the hardness, accuracy or surface quality. Therefore, we looked at this characteristic in phase 1 to model the correct product characteristics in the DRP. Based on our approach, it is not essential to know exactly the technical solution. Instead, we focus on the relevant characteristics that support understanding the real potential of the future possibilities of the technology. The evaluation criteria are the value creation and cost properties defined in phase 2. The evaluation also supports understanding the changes needed in the product and seeing the scope of the new design task.

Exploitation of the technology is evaluated in two steps. In the first step, an experienced designer who has the best knowledge of the product and its dispositions evaluates the technology. The second step is to evaluate the potential of the technology with a technology expert if one is available. Combining the views of these two groups gives a comprehensive understanding of the technical potential of the technology in the defined scope. The recognized potential of the technology is evaluated in monetary terms in the next phase.

3.5 Communicating the Value of the Technology

The fifth and final step is to estimate the business effects of exploiting the technology. The focus is to evaluate the monetary effects of recognized value creation mechanisms from the previous phase. The business impact is analyzed in a workshop with the same group for the CSL framework. The valuation of the technology should be done in a holistic view through the company. The real picture of the effects of the technology will not be shown if only one area is evaluated. Therefore, representatives from all relevant departments are requested. The proposed method allows using a wide perspective in the valuation of technology. At the same time, it is possible to evaluate changes in the company's business and the customers' or suppliers' businesses. Intangible values, such as safety, can be evaluated through the proposed method if the disposition between technology and safety is recognized during the process.

Evaluation is done in the order of the phases of the product life cycle from design to disposal. The product life cycle phases can be found in the CSL framework. Estimations of monetary effects are allocated to specific life cycle phases. A more detailed analysis can be done, for example, using partition of time, quality and amount of sell according to company policies. In addition, different technical solutions can be compared based on the same principles. Estimates of monetary sums are done in rough magnitude of order, EUR 1 000, EUR 10 000 and so on. The idea is to find the maximum potential yearly effect related to the current situation and business. Evaluation of the business impact also needs information about production numbers and other related financial data.

4 Case: Metal Coating with AM in Rock Drills

In this research, the method was tested in the real industry environment. The case study was performed in a global original equipment manufacturer (OEM) in the mining business. The technology to be explored was metal AM printing and especially coating techniques. Steps of the proposed method are used to show the case and the results of specific phases.

Phase 1: The main target was to improve the performance of the product instead of cost savings. Therefore, the focus was the properties defined by the user of the technical system. The technology was the AM coating, and we examined the characteristics related to the surfaces of the parts.

Phase 2: The CSL framework was modeled in a workshop according to the method description. Based on selections done in the previous phase, the main focus was to recognize the properties defined by the user of the rock drill: the drilling speed, hole straightness, energy consumption and drill steel life. See Figure 1.

Phase 3: The idea of the DRP is to link the characteristics of the product to the properties defined in phase 2. In this case, the DRP was extensive because of the selected technology. Product characteristics have to be modeled until the individual parts and surfaces appear to understand the effects of the surfaces of the product. This approach and the selected technology limited the evaluation of significant structural changes in the product. The analysis focused on the current function principle and structure. Designers involved in creating the DRP were interested and active participants. During the process, the common understanding of the product and design was improved.

Phase 4: In the evaluation of the exploitation of the technology phase, the designers and technology experts recognized two potential areas for the coating. More detailed research revealed that the recognized value could not be captured only by using AM coating techniques. Other parts and the structure of the product prevent the practical benefit of the planned technology. The main outcome of the case was that the explored technology does not have common characteristics with the product. Positive value creation mechanisms were not recognized during the evaluation process. To benefit from the AM technology, the product should have new structures or function principles that can be supported by AM characteristics.

Phase 5: Monetary estimation of the effects of the surface coating were done although the technical potential of the technology was unfavorable. The planned design solution was evaluated with managers of all related areas of the product life cycle. The new solution was minor and caused changes only in the production process in the product life cycle. In the case of the AM coating technology, one step has to be added in the manufacturing process, and it will increase the cost of the product.

5 Discussion and Conclusion

In this paper, a method for evaluating a new technology was developed and tested in the industry environment. The novelty of this research is to explain and show value creation mechanisms for technology. The research question was focused on gathering and structuring the information needed to evaluate the technology. The proposed method is a five-step method. The information gathering starts with the targets and continues toward technology exploitation possibilities and monetary estimation of effects. The main source of information is company personnel, and information is gathered in workshops. Selected theories and the research method provide relevant answers to and explanations for the phenomenon of the value creation of the technology. As the case study shows, the method is dependent on available design knowledge and the structure of the product. A totally new product concept can be evaluated if knowledge needed about the function principle is known. This method is generally related to the product, technology or business environment. The future research agenda is to perform more case study research related to verifying and developing the method for additional applications for practical purposes.

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PUBLICATION
III

Communicating the design knowledge to support technology management in the manufacturing industry: an application of pragmatic constructivism

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Abstract
The aim of this paper is to the advance pragmatic constructivist understanding about communication in the product development context. In particular, the paper provides new understanding about how proactive truth about design knowledge can be constructed and communicated within product development actors. The paper shows how company representatives in the manufacturing environment, e.g., managers and engineers can together understand the customer-value-creation mechanisms of a specific product and integrate their expert knowledge into visual form. Building the collective understanding requires communication between these actors. Ultimately, the actors may be able to construct a useful proactive truth about related business potentials and thereby support technology management in the product development context.

Keywords: communication, fact construction, technology, design knowledge, design reasoning pattern.

1 Introduction

> "Communication is part of every job and every role we play. It carries bits and pieces of reality constructs around between people. It connect actors and merges their reality constructs to create and maintain practices by encompassing construct with which they cooperate, understand and trust each other. […] By means of communication we can cooperate and organise complex processes. Without communication that would be impossible." (L. Nørreklit, 2017, p. 48)

The aim of this paper is to advance the pragmatic constructivist (PC) approach by increasing understanding about communication in the product development context. The goal is to answer the question: *how can product development* *actors communicate purposefully to construct factual possibilities about new technologies?* This question is highly interesting in terms of both developing practice and theory. Our approach is to bring together and seek synergy from two different field of research to address the research question: PC and engineering design science. Theories and practices from engineering design science support the understanding of technology in technical sense while PC supports the understanding of human behavior in complex environment, such as in the manufacturing industry. In management accounting research, PC has advantages related to other approaches such as taking human values into account (in contrast to, for example to actor network theory, see Jakobsen, 2017). Using PC also contributes to the practical relevance of our research paper (Mitchell, 2017).

First, in practice, technology evaluation is action that evaluates the future possibilities and possible scenarios related to technology in specific environment. Trying to understand and foresee the effects of technology (i.e. constructing the proactive truth) is highly related to expert knowledge, opinions and feelings (Boer et al., 1998; Braun, 2005; Park & Park, 2004; Dissel et al., 2009; Scheiner et al., 2015; Laine et al., 2016a, b; Lingens et al., 2016; Winter and Lasch, 2016). In other words, the current understanding and beliefs of relevant actors guide the evaluation of technology in a certain context of practice. Consequently, human action is not determined by natural laws (Trenca & Nørreklit, 2017) which, however, also might be objects of discussion in technology-related decisions.

Second, in terms of theoretical development: a core idea in PC is an actor's reality construction that is dimensioned by facts, possibilities, communication and values (e.g., Nørreklit et al., 2006; Nørreklit et al., 2010; Jakobsen et al., 2011; Nørreklit, 2017). The recent study by Trenca and Nørreklit (2017) calls for further research on organizational performance management in complex cases, with their particular interest in analysing actors' specific ways of reasoning. Oftentimes, the context of product development is considered complex from the viewpoint of management control (e.g., Jørgensen & Messner, 2010), which makes the study of collective fact construction and communication in the product development context particularly interesting (see also Laine et al., 2016b). Some pragmatic constructivist studies in the product/service development context already exist (e.g., Jönsson & Johansson, 2011); Laine et al., 2013; Mitchell et al., 2013; Rantamaa et al., 2014; Laine et al., 2016b; Korhonen et al., 2016; Laine et al., 2017; Leotta et al., 2018). However, no integrative methodology for understanding communication that underpins the construction of factual possibilities in research and development (R&D) has been proposed. This is the case, although specific communicative tools, such as boundary objects and boundary subjects have been proposed to facilitate knowledge integration (Laine et al., 2016b; see also Huzzard et al., 2010; Azambuja & Islam, 2018).

Moreover, prior research in pragmatic constructivism, and particularly on the communication dimension, makes a call for further research on managerial processes in complex environments. Indeed, more research is needed to understand the "genome" of managerial work and the communicative processes therein (and even on the long-term realization of related impacts, in Jönsson & Johansson, 2011). In all, our focus in this paper is on communication, to further understand the communication that would be necessary in technology management.

This paper addresses this challenge by using a real-life case study of an industrial company in which product design knowledge is integrated using a tool called the *Design Reasoning Pattern* (DRP, Lehtonen et al., 2016). The real-life case study shows how the DRP could facilitate determining factual possibilities and realizing purposeful communication. The DRP is a tool that can be used as a structure for constructing information about factual possibilities of product features through their dispositions in relation to other aspects of the production system, which they are eventually manufactured and put to work in (Mämmelä, et al., 2018b). Here, dispositions are defined as the proactive truth (or predictions) about the link between a product feature and the respective future product life cycle and value capture therein. Consequently, each design decision (concerning technology in this context) may affect a product feature, which in turn might necessitate iterative knowledge integration – studying which pragmatic constructivism could be a useful approach (Korhonen et al., 2016; Laine et al., 2016b; Rantamaa et al., 2014)

The presented technology evaluation method with DRP forms a basis for shared understanding about factual possibilities of technology and commitments the actors which supports the task execution (H. Nørreklit, 2017), which represents our theoretical contribution (to pragmatic constructivist understanding on communication). In this research the PC is mainly used as a method theory (Lukka & Vinnari, 2014) which provide tools to understand factual possibilities related to technology. However, as our paper contributes to PC as well, in particular with regard to communication, we could see PC both as a method theory and as a domain theory. The paper acknowledges that also understanding about the motives (values) of actors in organizations needs to be considered to support technology decisions. We are therefore presenting the particular perception of how to integrate four dimensions of pragmatic constructivist approach i.e. generating new company level topoi concerning technology decisions (H. Nørreklit, 2017).

This paper applies the pragmatic constructivist methodology for analyzing communication in product design work in the manufacturing industry, to understand how actors (by using the DRP) use a thorough evaluation of factual possibilities and how they systematically consider the effects of action or a decision – thus attempting to understand the triggering events of intentional action (L. Nørreklit, 2017). As a managerial implication, we are interested in supporting managerial work related to technology decisions, in the manufacturing industry. The systematic use of design knowledge in constructing causality, as in the DRP, to support technology-related decisions forms the main managerial implication of this paper. By using DRP, actors can construct and integrate knowledge about the facts and possibilities upon which new products or product features are designed. To provide meaningful results, sufficient design knowledge is necessary for using the DRP approach, underlining the need to integrate accounting information (business impact estimates, component costs, etc.) with technical knowledge (structural engineering, manufacturing, etc.). As a practical implication, the paper supports the understanding of the value creation mechanisms of technology in specific business environments.

Altogether, the value of this paper is to show that the pragmatic constructivist approach can support the technology decisions in the manufacturing industry by considering the values of humans in the part of organization and using the best available design knowledge to construct the causality. So far, such understanding, in the area of design research, relies largely on technical facts; thus, this paper contributes to the area of design research as well.

2 Literature review

2.1 Communication in pragmatic constructivism

According to Hall (2010) managers use monetary (accounting) information primarily to develop knowledge of their work environment, secondly it is one part of wider information set to perform their work and thirdly managers use verbal forms of communication rather than written reports. Communication brings the actors together, to understand the common managerial task:

> "With infinite amounts of information available and with very little time for analysing the possibilities of having values fulfilled, human beings need practical and systematic ways of generating opinions. This is why, on the basis of their life experience and learning, people develop specific ways of reasoning in communication." (L. Nørreklit et al., 2006, p. 48)

Indeed, it is essential to create viable forms of communication. But what is *communication* from the pragmatic constructivist viewpoint? L. Nørreklit (2017) refers to earlier work by Arbnor and Bjerke (2009), to present the process of communication as subjective reflection of a construct by an individual actor, analysis of the construct by actors involved, externalisation their perception of the construct to others, and even objectification of the construct to a widely accepted definition (see also Henriksen et al., 2004; Nørreklit et al., 2010). Later, constructs can be materialized into artefacts of purposeful type (Henriksen et al., 2004; L. Nørreklit, 2017). However:

> "Although communication conveys perceptions of facts, possibilities, reasons and values among people, communication does not, by itself, uniquely determine what people actually do." (L. Nørreklit et al., 2006, p. 58)

This is why actors still determine how they act, based on their reality construction. Communication is a way to build a common, valid reality construction, based on which actors then decide to act in the way they do. From the viewpoint of this paper, it is particularly interesting which kinds of tools/methodologies of communication could support managerial work in the product development/design context. In other words, we are interested in which kinds of communicative practices could support building up a common reality construction that is valid, in the product development/design context. Indeed, as Laine et al. (2013) see, there is indeed insufficient knowledge of communication in the product development context, particularly concerning the monetary expressions of value (e.g. accounting information). Fortunately, some earlier studies in pragmatic constructivism actually provide some background understanding about communication in the product development context. Specifically, such recent pragmatic constructivist research includes the work of Jönsson and Johansson (2011), Rantamaa et al. (2014), Korhonen et al. (2016), Laine et al. (2016b), Laine et al. (2017) and Leotta et al. (2018).

Jönsson and Johansson (2011), choose to understand communication in the product development context as probes that mean statements that actors make to focus collective attention to significant dimensions by questioning prior understandings and making assertions. The idea of such collective sensemaking in product development has also been acknowledged outside pragmatic constructivism (Laine et al., 2016a), and therefore **communicative probes** could be a viewpoint that could be useful for a wide academic audience. Rantamaa et al. (2014) link communication to **knowledge integration** in product development (see also Laine et al., 2016b). In the paper by Korhonen et al. (2016), communication is concerned with profitability information that supports new service development. Laine et al. (2016b) suggest the use of **boundary subjects** to bridge function borders and write that:

> "There is a clear need for enhanced theoretical understanding of the social process of choosing, constructing, elaborating and communicating accounting facts in the PD [product development] context because of the limited understanding of current PD accounting and control practice and the contextual requirements of PD for interaction between different actors and actor groups." (p. 308)

Laine et al. (2017) notice different top-down and bottom-up **modes of communication** in product development, and also the central role of product development project managers as **communication hubs**. Furthermore, they highlight important

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messages such as bringing up uncertainties and surprises to a relevant group of actors, and state that "enhanced communication among NPD [new product development] management actors would mean (or require) **co-authorship** and increased attention to **intentional (joint) construction**" of common topoi (Laine et al., 2017, p. 129, emphasis added), i.e. the "concepts and arguments applied in a specific setting" (L. Nørreklit et al., 2006, p. 43)

Furthermore, Leotta et al. (2018) see communication to take the form of accounting information to **verify** if R&D projects and strategies are aligned. In all, it seems the pragmatic constructivist literature underlines the importance of communication but in many studies, communication itself is not thoroughly examined. Indeed, no integrative methodology for communication that underpins the construction of factual possibilities in R&D has been proposed. Therefore, this paper attempts to increase understanding about communication in the product development context, by proposing a methodology for collective sensemaking (Jönsson & Johansson, 2011; Laine et al., 2016a) and knowledge integration (Rantamaa et al., 2014; Laine et al., 2016b), including:

- Co-authorship (Laine et al., 2017) and knowledge integration (Rantamaa et al., 2014; Laine et al., 2016b)
- Boundary subjects (Laine et al., 2016b) and communication hubs (Laine et al., 2017)
- Communicative probes (Jönsson and Johansson, 2011)
- Modes of communication (Laine et al., 2017)
- Communication as a vehicle for verification (Leotta et al., 2018).

2.2 Technology from a systems perspective

According to Hubka and Eder (1996, p. 73) "The term Design Science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for design." TTS (Hubka & Eder, 1988) is a major part of Design Science and describes the nature and purpose of technical systems. Hubka and Eder describe the transformation system (Figure 1) and its elements by transforming the operand from an existing state to a desired state. A technical system is a key element of a transformation system but also human work and information are highlighted in this theory. Definition of technology (Hubka & Eder, 1988, p. 260) is linked to this understanding; "technology is the specific way of delivering an effect to an operand." Effects in this scope are material, energy or information. Formulation of such models could be seen as an attempt to form causal chains between selected items (L. Nørreklit, 2017).

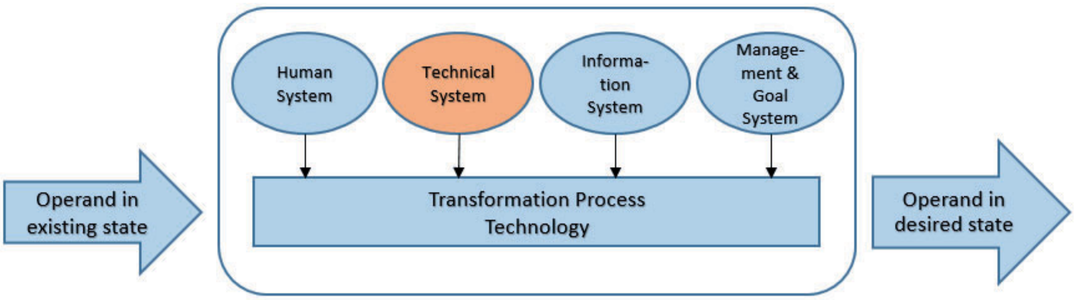

Figure 1. *The Model of the Transformation System in TTS (adapted from Hubka & Eder, 1988).*

In all, TTS provides a theoretical foundation about technical systems. It provides tools for evaluating and understanding the possibilities of technologies that relate to some products examined. TTS presents the idea that **the product** intrinsically has some specific properties, which cause its specific behavior. These properties, and thus behaviors, can be determined by a product designer, which is acknowledged in Property Driven Development (PDD) (see e.g., Weber & Deubel, 2003). The Design Reasoning Pattern (DRP) is a tool that can help actors understand, visualize and communicate the reasoning behind the designing of product. The DRP uses PDD approach (with a distinction between properties and behaviors of a product) as its guiding principle. In order to work, the DRP needs input, guidelines and targets from the business and customer environment – and from product designers to connect the design knowledge to product targets and values that guide work. Building this kind of a shared understanding with a systematic and fact-based approach can be the basis of the evaluation of factual possibilities. In all, from the systems perspective, our approach will focus on the product.

2.3 Technology from an actors' perspective

The main idea behind the pragmatic constructivist approach is to help actors in developing successful, functioning organizational activities in practice. The pragmatic constructivist approach includes assumption that actors always act "under presumption of a specific actor-world relation which they continuously construct, adjust and reconstruct in light of new experiences, context and communication." (H. Nørreklit, 2017, p. 5). This actor-world relation leads to reality construction. To form the reality construction, the four dimensions must be integrated: facts, possibilities, values and communication. Without facts, it is not recommended to make any decisions or actions. Possibilities are based on facts and they have to be known before reasonable actions. Values are needed for motivation and as driving force for actors. Real actions can be done only after communication, e.g., division of labor. (H. Nørreklit, 2017)

But what kind of a context is the product development/design context, from the viewpoint of pragmatic constructivism? One approach is that of technology management, since product development decisions often relate to technology. Generally, technology selection is seen as an important phase of new product development (NPD) activities for future success of firms. Therefore, technology choices are critical but still mandatory (strategic) decisions (Mitchell et al., 2013). Importantly, managers make technology decisions as a part of their managerial work. For related to technology investments, it is essential to try to understand the value of different technological options – also from the monetary viewpoint. What is technically possible is not necessarily economically, socially or politically possible and vice versa (L. Nørreklit, 2017). Some technology valuation methods that prior research recommends cover the **evaluation of the future possibilities of a technology** (Jang & Lee, 2013; Park & Park, 2004). However, we claim that to understand the future possibilities that relate to a technology it is compulsory to understand the **value creation mechanisms** (of that particular technology in manufacturing, in use at the customer, etc.) respectively. In other words, **causal dispositions** concerning technology are needed (L. Nørreklit, 2017). Technology evaluation methods that are based on understanding the product and value creation mechanisms of technology could therefore be beneficial for the product development/design practice (Mämmelä et al., 2018a; 2018b). In this paper, key elements that need to be recognized in a DRP to evaluate the **future possibilities** of technology exploitation are (Mämmelä et al., 2018b):

1. "Technical system intention and business intention";
2. "Product life cycle phases";
3. Desired behavior from life cycle phases;
4. "Product structure";
5. "Technology characteristics";
6. Dispositions between product properties and desired behavior;
7. "Potential effect of technology related to the product"; and
8. "Estimation of financial numbers related to the product".

Indeed, in this paper, information concerning factual possibilities is both **technical and accounting information**, since these naturally intertwine in new product development activities. Moreover, it would be important to look at all the above aspects 1-8 from a **proactive, actor-based viewpoint**, to actually realize the factual possibilities in new product development activities (Laine et al., 2017).

In this paper, our approach comprehends the product in the focus of communication. The reason behind this idea is that a product has specific life cycle phases which interact with departments and actions in the company. In other words, an action done in a company should enable fulfilling the product/business intentions. According to the Theory of Technical Systems (TTS) (Hubka & Eder, 1988), technical systems originate from humans needs; similarly, also valuable product or technology behavior also originate from the work of human actors in a context. That is a reason why the pragmatic constructivist approach can indeed support technology value creation in the manufacturing industry. However, as the selected focal areas for a specific technology valuation exercise are human constructs, natural laws selected for assessment in this exercise are a socio-technical choice (Trenca & Nørreklit, 2017). Such guiding principles can be captured only by constructing a specific understanding of actions and perceptions of actors in an environment. Pragmatic constructivism helps understand the motives of people and evaluate some of the possibilities related to new technologies. In all, our examination of technology management will include evaluating the future possibilities of a technology (Jang & Lee, 2013; Park & Park, 2004; Mämmelä et al., 2018b) by identifying the value creation mechanisms using causal dispositions (L. Nørreklit, 2017).

2.4 The framework of the paper: the application of pragmatic constructivism in product development/design

Based on the reviewed literature above, we can now build our framework. In practice, we will combine the pragmatic constructivist viewpoints to communication and technology management with the DRP. Indeed, the technology evaluation method used in this paper looks at the practical effectiveness by using the best available knowledge and understanding about the product and its design (Mämmelä, Juuti, Julkunen, et al., 2018). This kind of understanding originates from humans actors and it is challenging to study by using mechanist theories or approaches. Understanding also continuously improves during the evaluation process which can be seen a premise of pragmatic constructivism. (H. Nørreklit, 2017)

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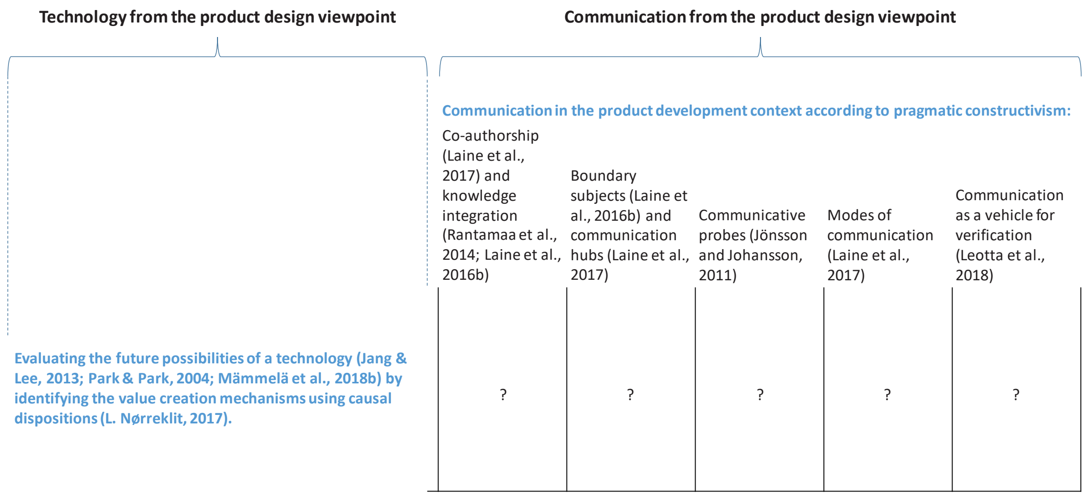

Figure 2. The framework of this paper (the question marks represent lacking knowledge).

In the following, we will show how the use of DRP will add to our understanding of communication in the product development context. Particularly, we will show how DRP contributes fact construction and knowledge dissemination, when, how, and by whom. This way we are able to answer our research question: *how can product development actors communicate purposefully to construct factual possibilities about new technologies?* Naturally, we acknowledge that the tools presented here are only one option, and thereby will describe the use of these tools with potential benefits as well as with possible obstacles.

3 Empirical results and case study

Design principles of used technology evaluation method are shared understanding, modelling tacit knowledge and using participatory methods. All these principles are executed in workshops where the people can communicate and thus form the common reality construction. To help and guide communication, the method focuses on the product and its properties and behaviour as a communication platform.

The main task of product development is to bring products to market through different processes, i.e. product life cycle phases. This means that a product has to behave in specific manner at different stages of product life cycle to be a "good" product. The desired behaviour of this product is related to the values and needs of its owner in each of the product life cycle phases (i.e., an actor that is in charge of the product and it's use in each phase: e.g., a car manufacturer, a car import company, a private car owner, a car wrecker at the scrapyard). Different values need to be converted into technical form (evaluation criteria) for evaluating a technical system. Such conversion represents **co-authorship**. TTS describes that the behaviour of the product is related to the properties of the product and between those properties are links, dispositions. Understanding the dispositions of a product is therefore central to communication in the product development context.

For example, the owner of a car expects that the vehicle is rust-free at least ten years form purchase. To fulfil this value expectation, the designer has to choose certain suitable properties to the product, i.e. here the car. The designer can choose to use, for example, aluminium instead of steel or using anticorrosive treatment. This example represents a simplified description of a real situation. However, there are also multiple different dispositions related to the decision of using aluminium: aluminium is (often) more expensive than steel and can therefore increase the product price.

In this section, the practical results of a case study are explained according to two different levels of communication in the managerial context of making technology decisions: using dispositions to understand the effect of technology (i.e. the evaluation of possibilities) and modelling the dispositions (i.e. fact construction). The presented case study took place in a global original equipment manufacturer (OEM) that operates in the mining business. In 2017, the OEM evaluated metal additive manufacturing (AM) coating technology in their rock drill business. To make decisions about technologies, managers need to have suitable understanding about the possible effects of technology related to business i.e. the value of technology based on technical potential of technology (see Figure 3).

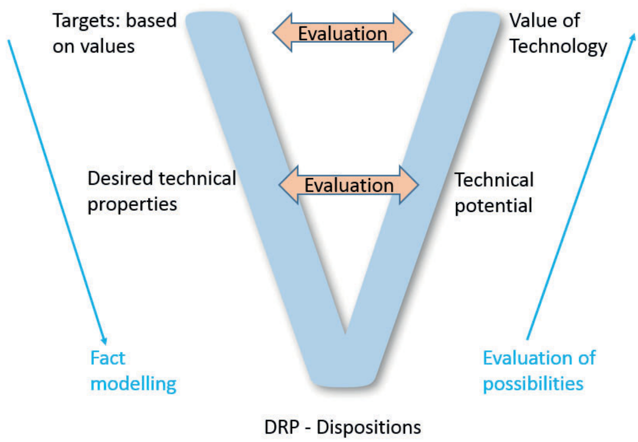

Figure 3. *Technology evaluation at the OEM.*

To manage complexity, the evaluation criteria have to be defined according to decision making principles (Ilori & Irefin, 1997). Again, the criteria are based on actors' values, but values have to be converted into technical properties for technology evaluation, i.e. targets are converted into desired technical behavior. Modelling the dispositions reveals the knowledgeable potential of technology, which actors evaluate against the defined evaluation criteria. Technical and monetary aspects are naturally taken into account in this evaluation method. Also at the OEM, while conducting certain evaluations, some managers preferred technical values and others relied on monetary estimations. Based on the case study, challenges in evaluating monetary values are highly related to sales estimations and market situations: the same product can have significant differences in sales between short periods of time. Moreover, from the viewpoint of the product, a technology incurs transformation through a technical system (Hubka & Eder, 1988). That transformation in the technical system needs to be converted into and communicated in financial terms based on certain business targets.

3.1 Making and communicating the business-oriented technology decisions

3.1.1 Fact construction

The first phase of technology evaluation, at the OEM, was to define the preliminary targets for technology exploitation plans. At the OEM, this target setting was done with the managers who are responsible for the technology decision, in workshops. Target setting is an important phase of starting the **reality construction and integration**; the preliminary targets should be up to date and agreed upon (to a certain degree) by related managers. Actors' values naturally influence the target setting phase: targets include intentions for the product and business and guide triggering events for intentional actions. At the OEM, those events were examined in the coming phases of technology evaluation and the effect of technology is evaluated according to mentioned events. Decisions in this phase concern for example technologies, business goals, products and general values. Usually top managers are involved when making such decisions, representing the **top-down mode of communication**. Values can include, among other things, choices between the best possible performance or environmental friendliness. Importantly, values may be shared (i.e. company value), but in any case, individual actor's possess the values making them subjective.

During the subsequent phases, the chosen values influence the properties of the technical system at the OEM. In the studied case, at the OEM, the focus was to improve the performance of OEM's products by using AM-coating techniques. The manufacturing cost of the product was not the primary target. Other choices done in this phase were the product and business segment selection.

3.1.2 Evaluation of possibilities

After target setting, subsequent technology evaluation phases support the monetary estimation by showing the potential value creation mechanisms and the possible product changes needed. This kind of comprehensive reality construction is rare in practice because of organizational boundaries and conflicting motives. In practice, technology value is evaluated according to change of desired behaviors, for example, 10% improvement of drilling speed can increase the sales or it can support increasing the price of the rock drill. In OEM's case, such estimates originated from their after sales department or other relevant people in a Business Impact Analysis (BIA) workshop. With AM technology, the change of manufacturing processes could also be discussed and evaluated; in OEM's case, manufacturing experts represented the most recommended people for that purpose. Thereby, these workshops represent the bottom-up **mode of communication**. Indeed, the final phase is the communication of technology value, which is done by using monetary estimation based the facts and estimations defined in previous phases. In this communication phase, there is a complete chain from technical properties and business intentions defined by managers to products. Communication makes it possible that the potential of a certain technology is commonly understood, based on the best knowledge available.

Table 1. *The communication focus in the managerial context.*

Communication focus	*Fact construction*	*Evaluation of possibilities*
What	Intentions regarding the product: what product(s) is under analysis? Intention regarding the business: what business is under analysis? Technology in general The main goal for technology exploitation	Monetary estimation of the technology based on recognized dispositions from DRP
Who	Manager(s) responsible for the technology decision and the facilitator of the evaluation (a boundary subject)	Manager(s) responsible for the technology decision and the facilitator of the evaluation (a boundary subject)
Why	To define the preliminary targets for evaluation To limit the scope of evaluation To guide participant selection to next phases	To construct the common reality: - possible technical effects of a technology - possible monetary value of a technology
Where	Target setting workshop	Business Impact Analysis workshop
When	When setting preliminary targets, in the beginning of a technology project (recommended)	When communicating the value of technology Before the final decision concerning technology selection is done (recommended)

In the OEM's case, there were no factual possibilities related to the selected technology. Results were as expected, i.e., the expenses increase by using AM technologies. Therefore, the final outcome of the evaluation exercise was that the technical benefits in this kind of product structure are hard to receive and without increasing manufacturing expenses.

3.2 Using dispositions as a tool for communicating the value of technology

3.2.1 Fact construction

At the OEM, reality construction was continued by describing the targets from the business environment. Facts were identified and the main targets for technology evaluation and input for DRP were given. Knowledge was related to the business environment of the selected product and business. Five key elements were recognized to describe the specific environment of product development in a Company Strategic Landscape (CSL): product structure, strategy, value chain, process and organization (Juuti et al., 2007). A CSL was used in this phase to facilitate the workshop in which related managers were involved. The process and the organization were the most static areas in the CSL; generally they are decided beforehand and cannot be changed easily. Strategy, value chains and product structures, contrastingly, are more dynamic, and based on the choices done by individual managers and guided those individuals' values. The most important outcome of the CSL workshop, in this case, was the attempted common understanding and managers' reality integration. The intentions and targets for technology exploitation were set and finding the triggering events could be started.

In case study, the targets were defined and converted into properties of the technical system. Transforming the values and needs of humans to concrete properties of a technical systems need reflections. This process requires communication between different parties. Because there are no direct links between human values and technical properties, this kind of inference is needed and it is based on the best available knowledge; highlighting the pragmatic approach. In the case, the value of improving the performance of a rock drill was interpreted, among other things, as increasing the drilling speed and operating efficiency. Quality of communication and understanding about the business were key aspects to be kept in mind when organizing a CSL workshop.

The CSL workshop was designed for managers who are responsible for an area of the product's life cycle. The assumption was that these managers would the best people to reflect upon the targets and how to reach the defined targets (see also Laine et al., 2016a; 2016b) – again representing **knowledge integration** and joint reality construction. An experienced designer can have a significant opinion about what is valuable or how things should be done. Therefore, the approach of using product properties and behavior is beneficial if the common understanding is seen valuable as it is in pragmatic constructivism. In the manufacturing industry, the commonly used Cooper's Stage-Gate model (e.g., Cooper, 1990) guides work mainly at the task level, i.e. not as specifically as product properties could. The Stage-Gate model also includes an assumption that managers make big decisions in the beginning of a product development project and more detailed decisions (like product properties) later. However, product development and the communication within are iterative processes in which targets and product properties need to be continuously aligned.

3.2.2 Evaluation of possibilities

In this phase, we have a construct and model our current understanding from human and business values to how the technical system fulfills our need through dispositions. Now it is time to communicate and start the evaluation of the possibilities of a specific technology, in a specific context. In the previous phases, we have set the targets and intentions for technology exploitation and communicated the triggering events related to desired behavior. After those tasks, evaluation of the factual possibilities take place, i.e. we are evaluating the potential effects of technology against targets. To guide this evaluation the best knowledge is collected to a DRP chart and subjected to systematic and logical evaluation. To support the evaluation both technology experts and designers evaluate the possibilities of a technology (**verification**). The main idea is to evaluate the potential change of product properties (caused by a certain technology) and evaluate the change of desired behaviors according to targets defined in the CSL workshop.

In the case study we recognized that the current product structure does not support using the AM coating. That is to say, desired benefits cannot be captured by chancing only the surfaces of the product. The product structure requires also other actions and modifications. Problematically, in OEM's case, there were no factual possibilities according to best knowledge related to AM coating. Table 2 summarizes the findings from this phase of technology evaluation.

Table 2. *Communication focus in with regard to technical aspects.*

Communication focus	*Fact construction*	*Evaluation of possibilities*
What	Converting targets from the business environment to technical properties Business: strategy, value chains, product, process and organization	The technical potentials of a technology related to desired properties and dispositions from DRP
Who	Managers of all related areas (design, manufacturing, supply, …) Facilitator of the method (a boundary subject)	Most experienced designers (verification) Technology expert (verification) Facilitator of the method (a boundary subject)
Why	To set clear targets for technology exploitation (desired properties) Guide the modelling of DRP Provide environment for communication with all related managers	To understand the technical potential of technology
Where	CSL workshop	Workshop
When	In the beginning of a technology project (recommended)	After the dispositions have been modelled in a technology project (recommended)

3.3 Modelling dispositions by using DRP as a type of communication

It is central to understand and describe the triggering events for intentional actions. This is done by understanding the properties of the product which the technology has an effect on. Figure 4 shows the simplified DRP-chart from the case study. The desired behavior is in the left and right side of the chart. Triggering events and product properties are in the product structure boxes. Targets and technology guide modelling of a DRP chart. This phase constructs most of the fact base related to technology evaluation. In the AM case we were only looking at the components surfaces because the selected technology has only effects on those components areas.

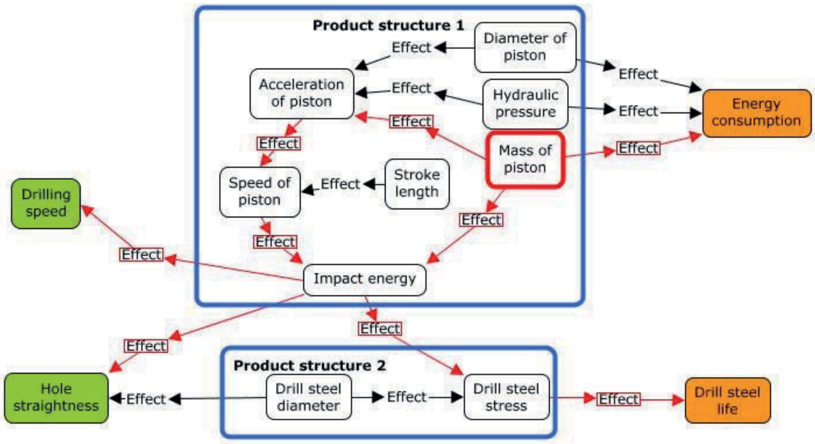

Figure 4. *An example of a simplified DRP-chart (adapted from Mämmelä et al., 2018a).*

A DRP chart is modelled with the most experienced designers and it is based on targets (desired behavior) and product properties. Modelling in reverse order guides the work and ensures that only the most influencing factors are shown in the DRP chart. This kind of modelling and communication between designers is uncommon based on the case study done. However, it could allow new types of **communicative probes**. The reason of the uncommonness of such modelling can be – as the case study shows – that even the most experienced designers have different reality constructs about how the object of design affects desired behaviors. In general, the understanding can be wrong but the disposition act as it is designed. This was the case for example related to the understanding about the shape of the globe; maps based on the flat globe worked fine even if the reality construction was wrong. Modelling and communicating the understanding by using a DRP is seen beneficial to evaluating the future possibilities of technology; and more importantly, to improve the understanding of a current situation. In practice, the DRP is modelled in multiple workshops (Table 3), first with individual designers and after the information seems saturated, the validity of a DRP chart is tested with (all) related designers.

Table 3. *Communication focus in technology evaluation.*

Communication focus	*Fact construction*
What	Dispositions between the product properties and behavior
Who	Most experienced designers available (recommended 2-4 persons) Facilitator of the method (boundary subject)
Why	To understand and model the possibilities of technology
Where	Workshops, with individual designers and validity tested with (all) related designers
When	After the targets are set in a technology project (recommended)

In all, our case study represents an in-depth examination of technology valuation. The empirical results show that communication among relevant actors is of utmost importance when evaluation both technical and monetary values, and presents ideas for facilitating design knowledge communication in the product development context.

4 Discussion and conclusions

In this paper, we have studied technology evaluation in the manufacturing industry based on the pragmatic constructivist approach. Figure 5 summarizes our empirical results from the viewpoint of the framework of the paper, and forms the basis of our contribution to pragmatic constructivism. As the figure shows, we can now supplement earlier studies by elaborating upon some aspects of communication in the product development context, particularly concerning technology decision making.

Technology from the product design viewpoint

Communication from the product design viewpoint

Evaluating the future possibilities of a technology (Jang & Lee, 2013; Park & Park, 2004; Mämmelä et al., 2018b) by identifying the value creation mechanisms using causal dispositions (L. Nørreklit, 2017).

Communication in the product development context according to pragmatic constructivism:

Co-authorship (Laine et al., 2017) and knowledge integration (Rantamaa et al., 2014; Laine et al., 2016b)	Boundary subjects (Laine et al., 2016b) and communication hubs (Laine et al., 2017)	Communicative probes (Jönsson and Johansson, 2011)	Modes of communication (Laine et al., 2017)	Communication as a vehicle for verification (Leotta et al., 2018)
Different values need to be converted into technical form (evaluation criteria) for evaluating a technical system. Such conversion represents **co-authorship**. Target setting is an important phase of starting the **reality construction and integration**; the preliminary targets should be up to date and agreed upon (to a certain degree) by related managers.	Facilitators of the workshop can be seen as **boundary subjects**.	Modelling and communication between designers is uncommon based on the case study done. It allows new types of **communicative probes**: even the most experienced designers have different reality constructs about how the object of design affects desired properties.	**Top-down mode:** Decisions concern for example technologies, business goals, products and general values. **Bottom-up mode:** There is a complete chain from technical properties and business intentions defined by managers to products. Communication makes it possible that the potential of a certain technology is commonly understood, based on the best knowledge available.	Most experienced designers are used for **verification**. Technology experts are used for **verification**.

Figure 5. *The framework of the paper revisited.*

In this paper, we now propose how actors could communicate when they make decisions regarding technology. We highlight the need to look at the DRP from a proactive, actor-based viewpoint, to actually realize the factual possibilities in new product development activities (Laine et al., 2017). The OEM's fact construction and possibility evaluation method was developed based on pragmatic constructivist ideas. First, target settings was needed. Then, modelling the value creation mechanisms of technology takes place together with constructing facts. After that, factual possibilities are evaluated from the technical perspective and finally, a monetary estimation is made based on collected information.

In all, the contribution of this paper is to form the causality from fact to possibilities of technology using best available knowledge of product and its design. From the pragmatic constructivist perspective, this paper elaborates upon communication in the product development context. Thereby this paper contributes to topical discussions on communication (see Figure 5). Each of the research strands on communication (columns) could benefit from our findings.

- Co-authorship can take the form of conversion of values into technical form, which adds to Laine et al. (2017).
- Target setting is emphasized for reality construction and knowledge integration, adding to Rantamaa et al., (2014) and Laine et al. (2016b).
- Workshop facilitators can serve as boundary subjects (corroborating and supplementing Laine et al., 2016b) and communication hubs (resonating with Laine et al., 2017) in a purposeful manner.
- Modelling of technical dispositions and communication among experienced designers might yield impactful communicative probes (elaborating upon Jönsson and Johansson, 2011).
- Both top-down and bottom-up modes of communication were witnessed (elaborating upon the findings of Laine et al., 2017).
- Communication is an important vehicle of verification, particularly by using design and technology experts opinions (resonating with Leotta et al., 2018).

However, the paper does not study, language games, for example. Such studies represent a relevant future research possibility in the area. How could language games be utilized in the product development context? How could productive practice be advanced by understanding language games better in product/technology management? For example, those are such questions that require further inquiry.

In practice, the paper shows that also understanding the motives (values) of humans in the organizations has to be considered to support technology decisions, which forms a contribution to design research. In other words, the systematic use of design knowledge in constructing causality to support technology decisions forms the main research implication from the engineering point of view. Therefore, sufficient design knowledge is necessary for using the developed approach. Practical implications of this research include supporting the understanding of the value creation mechanisms of technology in a specific business environment. In this paper, the main tool for understanding and capturing the value creation mechanisms of technology is the DRP-chart in which the best available design knowledge is modelled. Targets and intentions are defined by managers and transformed into technical properties. Connections between product properties and behavior is based on designers' understandings and views. Modelled value creation mechanisms are used to evaluate the factual possibilities of a technology and further evaluate the monetary effect of that technology, based on actual technological choices. A reality construction can be developed and focused by using the DRP.

We used pragmatic constructivism to improve and give usable explanations about the complicated environment, which is the case in manufacturing industry and accounting (L. Nørreklit, 2017). The nature of technical systems also originates from the needs of humans and any general value or properties cannot be defined (Hubka & Eder, 1988). The theory base of TTS lead us to model and understand the intentions of the examined company, which originate from the people working in the company. We need understand the value creation mechanisms from technology to intention because technologies have effects on the product and the product has an effect on a business and thereby fulfilling the business intention. There are no any physical or rule-based connections between those elements (people, business, products, technologies), but instead, the connection is formulated based on best available design knowledge and understanding of the operational environment. In the industry, many people and parties have different motives and goals. The method presented in this paper integrates the different viewpoints and communicate the factual possibilities of technology.

Since accounting facts can easily relate to design facts in product development (i.e. a physical product can be a central part of a business model), in this paper we claim that there is importance in examining the product design facts from the viewpoint of pragmatic constructivism. The pragmatic constructivist methodology on communication could even draw inspiration from some of the ideas presented in this paper that stem from the engineering approach to communication in product development. It is essential to determine the factual possibilities that exist in the reality of new product development – and importantly, not by speculation but by systematic and thorough thinking with logical reflection about the causal dispositions of new product development activities and their inputs and outputs (L. Nørreklit, 2017).

Finally, this paper shows that the pragmatic constructivist approach can support technology decisions in the manufacturing industry by considering the values of humans as a part of organization and using the best available design knowledge to construct causality.

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IV

Technology Valuation Method for Supporting Knowledge Management in Technology Decisions to Gain Sustainability

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Technology Valuation Method for Supporting Knowledge Management in Technology Decisions to Gain Sustainability

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Abstract: New technologies have major effects on the profitability of companies and the economic growth of society. If appropriate technologies can be routinely selected, then it is possible to achieve sustainability at a company level. Knowledge management (KM) can be used to support technology decision making and give an understanding of the potential of particular technologies in a specific business environment. In this study, the design research methodology (DRM) is used with three case studies in an industry environment to develop and evaluate a novel technology valuation method (TVM). The proposed six-step TVM focuses on the acquisition, modeling, and validation of product-related knowledge to support KM related to technology decisions. The contribution of this research is to use distinctions between product properties and behaviors with a disposition toward understanding the potential of technology. During the process, tacit knowledge is made visible and documented, which supports the reliability of technology decisions and enables companies to gain sustainability.

Keywords: technology; technology decision; knowledge management; manufacturing industry; technology valuation; sustainability

1. Introduction

All companies pursue economic sustainability. Sustainability has three overlapping components: economy, society, and environment [1]. The economic aspects are the focus of this research. Economic sustainability refers to "the capacity of the firm to be profitable not only today but also tomorrow" [2]. Environmental sustainability focuses on upholding the ecosystems that provide the resources and services needed by current and future generations [3], while social sustainability concentrates on communities and the processes associated with creating healthy communities [4]. The aim of this paper is to propose a novel technology valuation method (TVM) to support knowledge management (KM) in technology decision making in the manufacturing industry to gain sustainability.

Technology influences the profitability of companies and the economic growth of society [5,6]. This emphasizes the need for the successful management of technology. The main aims of KM are to create value for customers and to gain competitive advantages [7]. This paper focuses on the acquisition and use of knowledge related to technologies to evaluate the potential of a particular technology from the perspective of the company that is acquiring it. Technology valuation refers to the direct output of valuation methods (i.e., an evaluation of the potential of a technology), while the pricing of technology involves determining the price of acquiring the technology [8]. Technology valuation is one element of the technology decision-making process, which includes five steps: defining the alternatives, identifying the alternatives, determining the criteria, evaluating the alternatives, and choosing the best alternative. This process can also apply to technology decisions [9]. Technology valuation supports the steps of determining the criteria to be used to evaluate the alternatives, then evaluating the alternatives. Ilori and Irefin [9] describe various approaches to decision making; the current research uses a rational analytic approach, which is suitable for problems that are complex and important, as in the case of technology decisions.

Generally, three asset valuation approaches are recognized: cost, market, and income [10]. The income approach is the most frequently recommended [10–12] in technology valuation. The income approach considers the future earning potential of a technology based on expected future benefits [10]. To evaluate the future benefits, several methods have been proposed; however, the reliability of the knowledge used by these methods and the reasoning behind the knowledge have not been adequately explained. Most of these methods assume that expert knowledge is reliable. Chiesa et al. [13] state that the "limitation of monetary methods descends from their quantitative nature ... despite the objectivity of the procedure's results, they suffer from the assumptions made during the estimation of the parameters." According to Dissel et al. [14], many decisions are still made on the basis of expert judgment and gut feelings. Dissel et al. [14] highlight the motivation of this research, concluding that "further work is needed to understand how best to integrate the outputs into the broader technology investment processes in the firm." Our motivation is to use and implement theories from engineering design research in technology valuation to improve the valuation reliability. We are attempting to model the interplay between technology, products, and their lifecycles, and to validate the model within the TVM. This is achieved by making assumptions about the dependencies between product properties and the behaviors of products during their lifecycles.

Based on the above-mentioned references [10,11,14], the research gap is that technology valuations are mostly based on assumptions. The aim is to improve the reliability of the knowledge used in valuation and to ensure that the reasoning behind a technology decision is visible and evaluable. To address the knowledge-related gap in technology decisions, the proposed TVM focuses on product and design knowledge, since technology affects through products [15], and products affect business and sustainability [16–19]. The knowledge regarding the relationship between product properties and behavior is key to the proposed TVM. In order to describe the required knowledge, acquire this knowledge from individuals and organizations, and use this knowledge to support technology decisions, the following research questions (RQ) were set:

RQ1: What is the key individual and organizational knowledge needed in technology valuation to make the assumptions visible in order to support sustainability?
RQ2: How can the key individual and organizational knowledge be acquired?
RQ3: How can this key individual and organizational knowledge be used in decision making?

These questions were answered using the design research methodology (DRM) [20] and three case studies [21] that were conducted in the real industry environment of an original equipment manufacturer (OEM) in a mining business. Our aim was to research the acquisition and use of knowledge related to technologies in the manufacturing industry. To choose the case company, we had three criteria: (1) all critical knowledge had to be available; (2) researchers required access to the data; and (3) we would be granted permission to publish the results. The selected case company fulfilled all the criteria and was chosen in order to facilitate a successful research project.

The main contribution of this research is to focus on products and especially on the distinctions between product properties and behavior in KM in technology valuation and decision making. A practical TVM is proposed, which constitutes the main managerial contribution of this research. By using the TVM, it is possible to improve the reliability of technology valuation and thus make sustainable technology decisions. The proposed TVM is based on understanding the product properties and behavior to describe their dispositions. Therefore, if the products and technologies being evaluated do not have these dispositions, or if the required knowledge is not available, this method cannot be used.

The structure of this paper is as follows: The introduction is given in Section 1, followed by the literature review discussing KM and engineering design research (EDR) in Section 2. A scientific approach is discussed in Section 3, the results of the research in the form of proposed TVM are given in Section 4, and a general discussion and conclusion are in Section 5.

2. Literature Review

In this section, theories regarding KM and EDR are discussed from the perspective of supporting technology decision making. Our aim is to develop and propose a practical method. Newell [22] describes the method with four statements: it is a specific way to proceed, it is a rational way to proceed, it involves subgoals and subplans, and its occurrence is observable. These statements guide the development of the proposed TVM, and the fulfillment of the criteria are evaluated in the discussion in Section 5.

2.1. Knowledge Management (KM)

Lloria [7] has done a comprehensive review of the main approaches to knowledge management, and based on that review, KM is a broad concept that includes the following aspects:

1. It "is related both to business practice and to research". The authors researching KM come from various disciplines, providing important insights, but on their own no individual author provides an integrating framework.
2. It "goes further than technology management or information management". Tacit knowledge, human intervention, and learning are the key aspects, rather than information technology.
3. It "is a broad concept, and is made up of different activities", including, among other things, the creation and application of knowledge.
4. It "is principally found in people and is developed through learning". Knowledge should evolve from a human asset to a business asset.
5. Developing new opportunities, creating value, or obtaining a competitive advantage are possible aims for KM.

Research on organizational learning and KM can be described as levels of KM outcomes (creation, retention, and transfer) and KM context (properties of units, properties of the relationships between units, and properties of knowledge) [23]. A three-dimensional model for describing the framework of KM was presented by Choo and Neto [24], who added the enabling condition level to the aforementioned outcomes and context. The influence of knowledge, innovation, and technology management capabilities on research and development are examined by Asim and Sorooshian [25], and three types of capabilities are highlighted: process, infrastructure, and strategic. This paper focuses on all three of these outcomes, and in the context of KM, the levels of units (individual and organizational) and knowledge are put under analysis. Argote, McEvily, and Reagans [23] emphasize the role of social relations and human factors in managing knowledge.

Different countries and regions have taken divergent directions regarding the development of KM. European companies focus on measuring knowledge, while American companies are concerned with management, and Japanese companies are approaching the task by creating new organizational knowledge. The origins of these differences in perspectives are, for example, how knowledge is understood, what the company does with the knowledge, and who the key individuals are [26].

Earl [27] considered KM strategies and schools in order to propose a taxonomy, and he identified several categories or schools. This present paper uses the systems-based technocratic school and the spatial-based behavioral school. The technocratic school is based on management technologies that support employees' everyday tasks. The fundamental idea behind this systems-based school is to capture specialist knowledge, which other specialists can then access. This is a means of capturing individual or group knowledge and sharing it for organizational use. The behavioral school is based on stimulating and orchestrating managers for effective KM. This spatial-based school concentrates on the use of space to facilitate the exchange of knowledge. The Japanese concept of "ba" is discussed in [28] as a fundamental condition for knowledge creation and KM, and it can be understood as having a similar ideology as the spatial school.

As described above, knowledge acquisition is an important aspect of KM. However, the knowledge transfer among individuals in a group must also be taken into account. Alavi and Leidner [29] present modes of knowledge creation between individuals that range from tacit to explicit. At the level of the individual, after the application of knowledge, it is possible to learn (i.e., increase) tacit knowledge. After this tacit knowledge is explicitly implemented (modeling and documenting), it is possible to transfer the knowledge to the group's sematic memory and vice versa. The transfer of individual tacit knowledge directly to the group's episodic memory is also possible [29]. Additionally, trust in management has positive effects on employee creativity toward achieving sustainability [30], which can be supported by knowledge transfers.

The above references are used to answer RQ2 and RQ3, regarding how knowledge is acquired and how it can be used. The proposed TVM strongly relies on the facilitation of knowledge acquisition.

2.2. Engineering Design Research (EDR)

In this subsection, theories from EDR that help to fill the gap in the literature regarding the reliability of knowledge are discussed. The aim is to show why product-related knowledge is important and should be efficiently managed if sustainability is to be achieved.

According to Hubka and Eder [31], "The term Design Science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for design." The theory of technical systems (TTS) [15] instead focuses on describing and substantiating technical systems (i.e., products), and TTS are one part of design science. The transformation system includes the main elements of TTS: inter alia, technical systems, technologies, and the transformation process. The need for transformation emerges when the current state is insufficient and the current state of the operand (Od1) must be transformed to the desired state (Od2). In practice, when the energy of fuel (Od1) is transformed to rotational energy (Od2) using a combustion engine, this transformation exists. TTS describes the nature and origin of products, which can be used to represent and understand technical systems.

To understand the effects of decisions made in the manufacturing industry, Olesen [19] presented the concept of disposition. Disposition is defined in the following way [19]: "By a disposition we understand that part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas." This concept asserts an understanding of the lifecycle phases of a technical system, since the product may influence all of the systems that it is subject to. In this paper, the term disposition is used to refer to the link between a decision being made—a technology decision, in this case—and the effects of the technology.

The concept of a disposition that is being presented is still highly theoretical, and more concrete tools are needed to support practical decision making. Two main activities during design are analysis and synthesis. Analysis signifies the process of determining a product's behavior from its known properties. Synthesis is the opposite process, whereby the product's properties are defined from a known or given behavior. In this context, product behavior is understood as, for example, the weight or price of a product, and its properties, such as wall thickness and material, can be directly influenced by the designer.

By combining previously mentioned theories and approaches, Andreasen [16] proposed that a product can be described using different domains, such as activity, organ, and part. In each domain, it is possible to use synthesis to reason backwards from behavior to structure. Similar models were developed by Gero [17] and by Weber and Deubel [18] in their property-driven development/design (PDD) theory. PDD focuses on the distinctions between product properties and behavior when developing and evaluating technical systems. In this research and in the proposed TVM, the PDD approach is used to describe the links between product properties and behavior.

Figure 1 presents the idea of using theories from EDR to support KM for sustainability. At the top of the figure, the economic aspects of sustainability are set as targets. Using PDD, it is possible to use synthesis and determine the desired behavior of a product and further the properties of the product that cause this behavior. Technology can only effect product properties, as demonstrated at the bottom of Figure 1. The dispositions are presented in the figure, using red arrows. The proposed TVM is constructed using the approach being presented. The texts of the smaller boxes in Figure 1 are derived from Case Study 1, which describes the kinds of matters that can be dealt with in each entity.

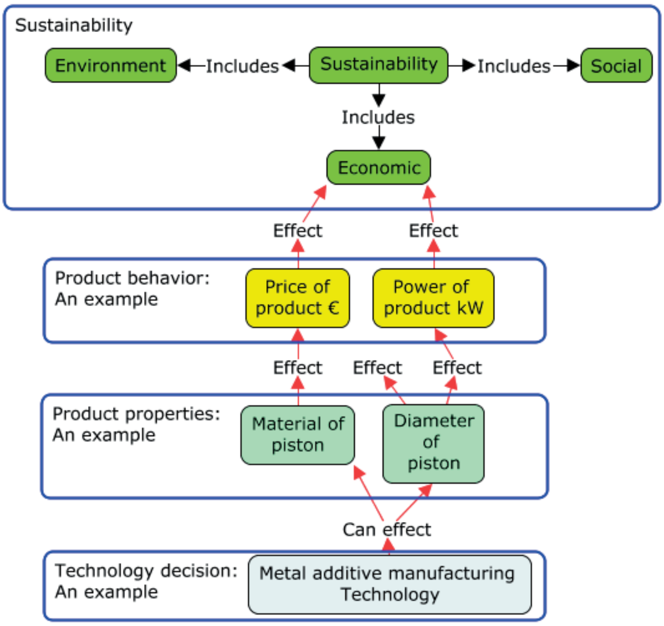


Figure 1. An example of the dispositions between technology decisions and the economic perspective of sustainability, based on engineering design research (EDR) theories.

Because the focus is on knowledge, the following eight key elements are needed to evaluate the potential of a technology [32]. All these key elements are based on EDR theories and are used as the basis for the proposed TVM:

1. Technical system intention and business intention
2. Product lifecycle phases
3. Desired behaviors from lifecycle phases
4. Product structure
5. Technology properties
6. Dispositions between product properties and desired behaviors
7. Potential effects of technology related to the product
8. Estimation of financial numbers related to the product

3. Materials and Methods

We have chosen to use qualitative research with a constructive approach, due to the nature of the phenomenon being investigated. Our aim is to visually model the assumptions of people, which is the best available knowledge in the early phase of technology evaluation. In this research, the DRM [20] is used to develop a method to support technology decision making in the manufacturing industry. DRM is a qualitative research method. Table 1 summarizes the research project (Type 3 [20]) according to the DRM and the research phases. The first phase of the DRM is research clarification (RC), which is based on a literature review and focuses on identifying the current research gaps and goals, including the RQs and the relevant disciplines (see Sections 1 and 2). The second phase is Descriptive Study 1 (DS-1), which improves our understanding of the selected research area and is also based on a literature review (Section 2). The prescriptive study (PS) focuses on developing the support needed to improve the current state. In this case, support refers to the proposed TVM, which aims to improve the reliability of the technology-related decisions; this is discussed in more detail in Section 4. Descriptive Study 2 (DS-2) is used for the evaluation and development of the TVM. RQ1 is answered based on the literature reviews of phases RC and DS-1. RQ2 and RQ3 include specific literature reviews, although the main focus is on the development of the TVM and its evaluation using the case studies in the PS and DS-2 phases.

Table 1. Steps of the research method, project type, and answers to the research questions (RQ1–3), according to the design research methodology (DRM) [20].

Stage	Research Clarification	Descriptive Study 1	Prescriptive Study	Descriptive Study 2
RQ1	x	x		
RQ2		x	x	x
RQ3		x	x	x
Type 3	Review-based	Review-based	Comprehensive	Initial
Main outcomes	Goals	Understanding	Support	Evaluation

The evaluation and development of the proposed TVM has been conducted using three case studies that employ a holistic multiple-case design (see Figure 2) [21]. Each case study has a different context, meaning different people involved, products researched, and targets.

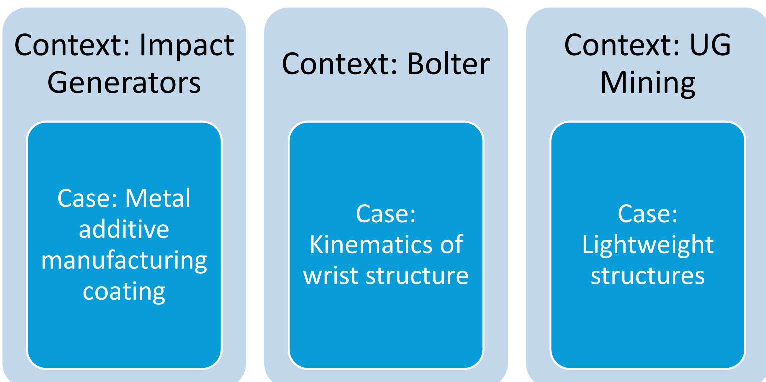


Figure 2. Multiple-case design used in case studies, adapted from [21].

The case studies were undertaken at an OEM in a mining business during 2017 and 2018. To choose our case company, we had three criteria: (1) all critical knowledge had to be available; (2) researchers required access to the data; and (3) we would be granted permission to publish the results. The selected case company fulfilled all the criteria and was chosen. Different technologies and business areas were selected to evaluate and test the proposed TVM, as shown in Table 2. The workload of each step of the proposed TVM is described in Table 2 to show the role of workshops in the proposed TVM. Each step of the TVM includes several workshops to acquire and model the required knowledge.

Table 2. Case studies undertaken during the research, evaluation, and development of the technology valuation method (TVM).

	A Metal Additive Manufacturing (AM) Coating for Impact Generators	The Kinematics of a Bolter Boom Wrist Structure	The Lightweight Structures of an Underground (UG) Boom
Case study	Case Study 1	Case Study 2	Case Study 3
Technology	Metal AM coating	Wrist structure concepts	Lightweight solutions
Evaluation focus of the TVM according to the DRM	Usability and applicability	Usefulness	Usefulness
Data collection time period	6/2017–2/2018	4/2018–11/2018	4/2018–12/2018
OEM representatives involved	Technology manager Designers (3) Manufacturing manager Manufacturing designer Technology expert (outside the organization)	Product managers (2) Design managers (3) Sourcing manager Technology manager Aftermarket specialist Designers (3)	Technology manager Product managers (2) Designers (3) Design manager
Total workload	98.5 work hours in 27 meetings with 7 different people	93 work hours in 15 meetings with 11 different people	56 work hours in 11 meetings with 7 different people
Step 1: Preliminary targets	Included in step 2 in this case study	2 workshops with 2 different people	1 workshop with 1 person
Step 2: Targets from a business environment	2 workshops with 2 different people	1 workshop with 8 different people	1 workshop with 8 different people
Step 3: Modeling dispositions	22 workshops with 3 different people	8 workshops with 3 different people	8 workshops with 5 different people
Step 4: Evaluation of the exploitation of technology	2 workshops with 4 different people	3 workshops with 2 different people	1 workshop with 4 different people
Step 5: Business impact	1 workshop with 2 different people	1 workshop with 1 person	This was not done in this case study
Step 6: Communicating the value of technology	Included in step 5 in this case study	By the facilitator	By the facilitator

Figure 3 presents the TVM evaluation and development procedure, including the case studies. The initial version of the TVM was developed in the RC and DS-1 phases, and was tested and evaluated in Case Study 1. After each case study, the TVM was evaluated and improved, if needed, and this was done three times after each case study. The proposed TVM is presented in Section 4.

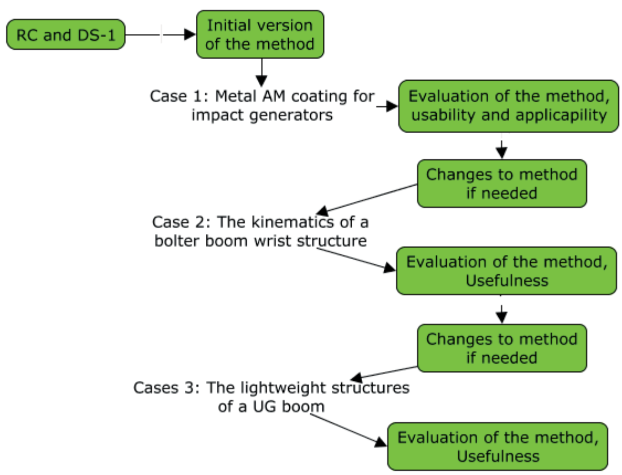


Figure 3. The TVM development and evaluation in each case study.

4. Results

A complete description of the proposed TVM is presented in Figure 4. The central column shows the method's steps in the recommended order of business, from top to bottom. On the left are the tools related to each step, mainly workshops with specific tools for acquiring the required knowledge. The outputs of each step and the inputs for the next steps are described on the right side and focus on the use of knowledge.

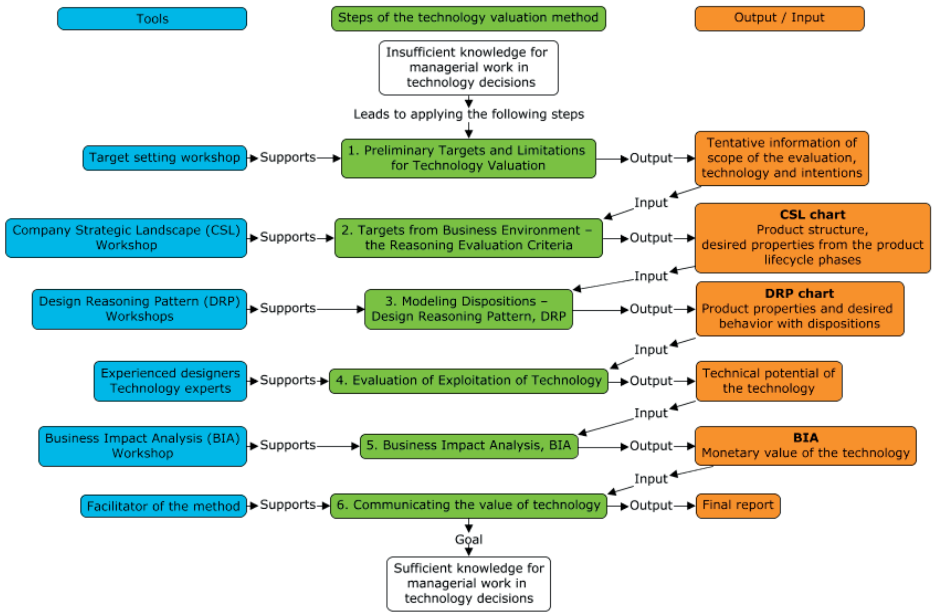


Figure 4. A description of the proposed technology valuation method (TVM), with the knowledge-gathering tools that are used and the outputs that document this knowledge.

Previous studies related to method and its development were undertaken, and the information needed to evaluate the value and cost of technology in the manufacturing industry was discussed in [32]. A method was formulated to acquire the eight key elements found in the previously mentioned research. The first version of this method was presented in [33] and included five steps. The difference between the first version of the TVM and the version proposed in this paper is the addition of the sixth step at the end. It is essential to communicate the value of technology in the form of a final report, where the acquired knowledge is documented and reusable. The following Sections 4.1–4.6 include a detailed description of the steps of the proposed TVM.

4.1. Preliminary Targets and Limitations for Technology Valuation

The purpose of this step is to discuss the preliminary targets and limitations for technology valuation in order to start the valuation process. The first step is conducted in a workshop where the responsibilities of technology decisions in the company are involved. This step focuses on exploring the acquisition of preliminary knowledge for businesses, products, technologies, and organizations and supports the formation of a common understanding among managers regarding the targets of technology. It also helps with the execution of the next step and the participant selection. The contribution of the first step to KM is presented in Table 3, where the knowledge type, key knowledge, acquisition of knowledge, and use of knowledge are shown.

Table 3. Contributions of step one of knowledge management (KM) for sustainability.

Knowledge Type	Key Knowledge	Acquiring the Knowledge	Using the Knowledge
Key individual knowledge	Intention of business Intention of product Organization being studied Technology properties	From manager(s) in target setting workshop	To form a shared understanding about the targets
Key organizational knowledge	Intention of business Intention of product Organization being studied	From manager(s) in target setting workshop	Selecting the relevant participants for the second step

4.2. Targets from the Business Environment—The Reasoning Evaluation Criteria

The second step of the proposed TVM focuses on acquiring the targets from the business environment and includes the goals for sustainability. The target setting step contributes to the decision-making process [9] by determining and reasoning the evaluation criteria. The targets are acquired in a company strategic landscape (CSL) workshop with management, as defined in step one. This CSL tool describes five vital elements of the business environment: strategy, value chains, products, processes, and the organization of a company (see Figure 5) [34,35]. Understanding the previously mentioned aspects is also seen as beneficial in the valuation of strategic production decisions [36].

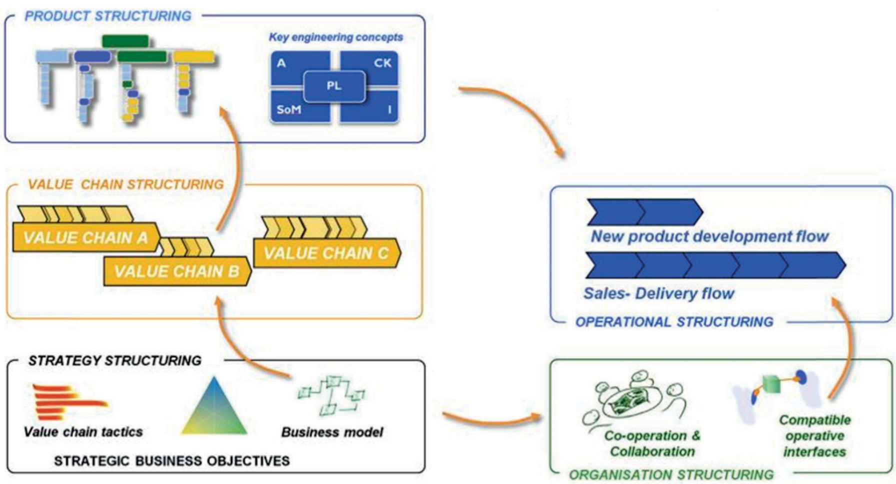


Figure 5. The company strategic landscape (CSL) tool, adapted from [35].

Knowledge acquisition begins with the strategy structure box shown in Figure 5, where the scope of the analysis is defined. The results of the first step provide a suitable base for the workshop, with the businesses, products, and organizations defined and available for discussion. The product or business owner generally has the best available knowledge regarding strategy. After the strategic and organizational goals are defined, the process of creating the product is discussed. This area of the CSL tool includes the lifecycle steps of the product in calendar order, including, for example, market research, product development, sales, and recycling.

Knowledge related to product structuring is shown at the top left side of Figure 5. Here, the aim is to split the product into suitably sized entities for evaluation purposes. Generally, the design manager can describe the product structuring used for design purposes, which can also be used in this analysis. Finally, value chains, the most interesting element of the technology valuation context, are discussed and documented within the CSL tool. A value chain is a desired behavior from the product's lifecycle phases; for example, the price or power of the product. Defining desired behaviors requires extremely specific knowledge related to the business environment. To form the value chains that were previously described, the product lifecycle phases can be used to support this phase. The owner of a specific product lifecycle phase can be asked "what creates value in your area?" For example, a sales manager may be more focused on the power of a product rather than the price of its parts (the focus of the purchase manager). The contribution of the second step of KM is presented in Table 4. The main focus of the second step is to achieve a common understanding of targets that are related to technology valuation. In the next step, the design knowledge is linked to the targets.

Table 4. Contribution of step two to knowledge management (KM) for sustainability.

Knowledge Type	Key Knowledge	Acquiring the Knowledge	Using the Knowledge
Key individual knowledge	Product lifecycle phases Desired behavior from lifecycle phases Product structure	From manager(s) in the CSL workshop using the CSL tool	To form a shared understanding of the targets
Key organizational knowledge	Shared understanding and common agreement of the priority of targets	From manager(s) in the CSL workshop using the CSL tool	Supporting the third step by providing the product structure and the desired behavior of the product

4.3. Modeling Dispositions—Design Reasoning Pattern (DRP)

In this phase, the targets from the business environment are set. In step three, the knowledge of the product and its design is used to communicate how the product fulfills its stated goalsFigure 6 shows the simplified design reasoning pattern (DRP) [37] chart from Case Study 1. The boxes at the top of Figure 6 show the final goals of the technology from the perspective of sustainability (safety, profit, and environment, in this example), which were defined in steps one and two of the TVM. On the left are the desired behaviors of the product (drilling speed and hole straightness) and the reasoning for how these behaviors generate income. On the right are the behaviors that generate costs (energy consumption and drill steel life), with the cost reasoning imported from the CSL tool. In the middle of Figure 6, in the large box with the blue outline, are the product structures, which were also defined in the CSL step.

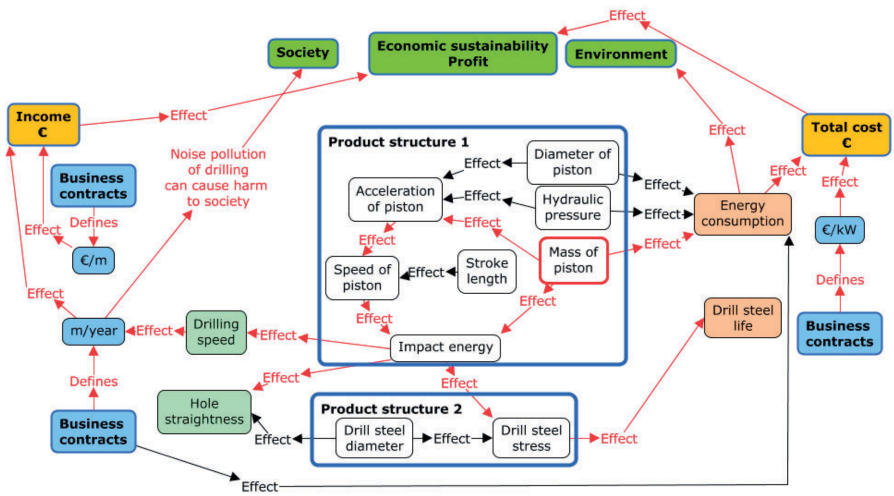


Figure 6. Simplified design reasoning pattern (DRP) example from Case Study 1.

The modeling of the design knowledge, including the distinction of product properties (the boxes in the product structure area) and the desired behaviors, is done with the most experienced designers in the area. The main focus is on understanding how specific properties cause the desired behavior and visualize the links and dispositions between them. It is recommended that several designers should be used when forming the DRP to ensure a comprehensive understanding of the knowledge used in the design. Table 5 shows the contributions of step three to KM.

Table 5. Contributions of step three to knowledge management (KM) for sustainability.

Knowledge Type	Key Knowledge	Acquiring the Knowledge	Using the Knowledge
Key individual knowledge	Dispositions between product properties and desired behaviors	From designer(s) in DRP workshops	To form a shared understanding about dispositions
Key organizational knowledge	Shared understanding and common agreements regarding the priority of dispositions	From designer(s) in DRP workshops	To evaluate the potential of technology in step four

4.4. Evaluation of the Exploitation of Technology

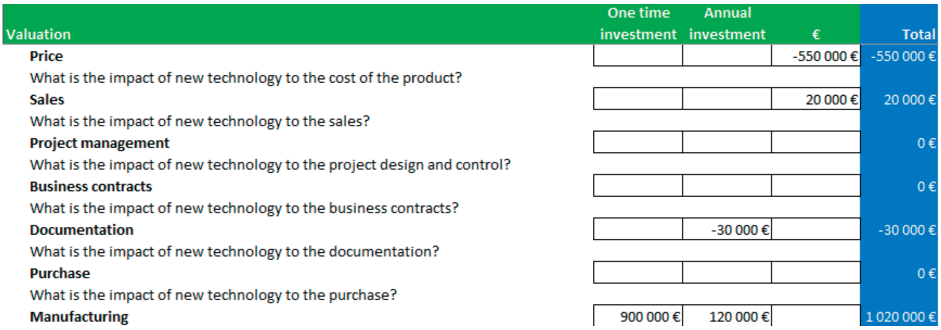
In step four of the proposed TVM, the potential of technology is explored, based on the acquired and modeled knowledge on the product and business environment. This is done in two phases—first, with designers, and second, with technology experts, if they are available. Here, the modeled DRP chart is used to support the evaluation. For example, in Case Study 1, the company was eager to find out the benefits of additive manufacturing technology in pulse generators. The current manufacturing technology is based on casting, thermal treatment, and machining. This leads to the technology valuation question formulated as follows: "What are the potential benefits of metal additive manufacturing in pulse generators?" The DRP chart was used to analyze the potential impact. Additive manufacturing potentially enables change in the mass of the piston. This change (see the "Product structure 1" box in Figure 6) has an effect on profit, according to the red arrows in the DRP. The red arrows are understood as dispositions, and the acquired knowledge is used to visualize the potential impact of technology. This step only shows the effects, while the magnitudes of the physical values and the monetary estimations are considered in the next step. The contribution of step four to KM is presented in Table 6.

Table 6. The contribution of step four to knowledge management (KM) for sustainability.

Knowledge Type	Key Knowledge	Acquiring the Knowledge	Using the Knowledge
Key individual knowledge	Properties of technology Potential effects of technology according to the modeled DRP	From designer(s) and technology expert(s) in the workshop	To form a shared understanding of the potential of technology
Key organizational knowledge	Shared understanding and common agreement on the potential of technology	From designer(s) and technology expert(s) in the workshop	To evaluate the monetary effects of technology

4.5. Business Impact Analysis (BIA)

The business impact analysis (BIA) is conducted in step five, where the potential of technology is evaluated from an economic perspective. The basis of the evaluation is formulated in the previous phases (i.e., where knowledge of the potential of technology is acquired, modeled, and validated). The recognized dispositions are valuated in a BIA workshop, using the BIA tool presented Figure 7. The product lifecycle phases that were identified in the CSL are shown on the left side of the tool, and the valuation is done according to company-specific criteria, such as quality, time, carbon footprint, or price, as shown in Figure 7.



Valuation	One time investment	Annual investment	€	Total
Price			-550 000 €	-550 000 €
What is the impact of new technology to the cost of the product?				
Sales			20 000 €	20 000 €
What is the impact of new technology to the sales?				
Project management				0 €
What is the impact of new technology to the project design and control?				
Business contracts				0 €
What is the impact of new technology to the business contracts?				
Documentation		-30 000 €		-30 000 €
What is the impact of new technology to the documentation?				
Purchase				0 €
What is the impact of new technology to the purchase?				
Manufacturing	900 000 €	120 000 €		1 020 000 €

Figure 7. An example of a business impact analysis (BIA) template.

The managers who were involved in the CSL workshop that defined the targets are recommended as participants, since they have the best knowledge regarding the potential effects of technology in the valuation context. The contribution of step five to KM is presented in Table 7.

Table 7. The contribution of step five to knowledge management (KM) for sustainability.

Knowledge Type	Key Knowledge	Acquiring the Knowledge	Using the Knowledge
Key individual knowledge	Accounting data Knowledge about business contractsEffects on product lifecycle processes	From manager(s) in the BIA workshop	To form a shared understanding of the economic effects of technology
Key organizational knowledge	Shared understanding and common agreement regarding the potential and business effects of technology	From manager(s) in the BIA workshop	Supporting decision making related to technology

4.6. Communicating the Value of Technology

The final step of the TVM is communicating the value of technology. In practice, this is the final report that documents the knowledge acquired during the process. From the KM perspective, this step enables the development of knowledge when it is available to the relevant participants. There are no specific guidelines regarding how this step should be carried out. It is dependent on company policies and the final use of the acquired knowledge. A summary of the knowledge related to step six is presented in Table 8.

Table 8. The contribution of step six to knowledge management (KM) for sustainability.

Knowledge Type	Key Knowledge	Acquiring the Knowledge	Using the Knowledge
Key individual knowledge	-	From documentation produced in steps one to five in the TVM by the facilitator	Communicating the knowledge related to the technology decision
Key organizational knowledge	Business targets (CSL) Design knowledge (DRP) Economic impact (BIA)	-	Supporting decision making related to technology and improving knowledge

5. Discussion and Conclusion

This paper proposes a novel TVM to support KM in technology decisions to improve sustainability by using approaches from design science [31]. The paper focuses on the acquisition and use of knowledge and the economic aspects of sustainability, as well as on societal and environmental aspects, which can be taken into account during the evaluation. Based on three case studies that were carried out, the TVM supports the acquisition and use of knowledge to improve sustainability.

The main contribution of this paper is its focus on the product, including the properties and behaviors of a technical system in KM, in order to make the assumptions behind the technology valuation visible and put them under analysis. Sustainability defines the business goals and targets of a product. The behavior of a product has a direct effect on sustainability—for example, the price of a product (economic perspective) or the contamination associated with a product (environmental perspective). The behavior of a product is caused by properties that the designer can directly affect. Technology can change the properties of a product, and by understanding the previously mentioned cause–effect link, it is possible to evaluate the sustainability of technologies in a specific environment. To gain sustainability, the TVM focuses on aspects similar to those of the methodology proposed by Battagello et al. [38] for supporting make/buy decisions: connectedness, strategic value, and magnitude.

Regarding the definition of the method by Newell [22], the TVM fulfills all four statements. The proposed TVM can be seen as a specific way to proceed, since it is focused on supporting technology decision making in product development toward sustainable goals in each business situation and environment. Second, it is based on design science [31], which strongly guides the proceedings. Technology decision making [9] defines logical steps, including the determination of criteria and the evaluation of alternatives where they are supported by the proposed TVM. Theories from EDR also support the rationale for the proposed TVM. A description of the proposed TVM is given in Section 4, and the subgoals and subplans of the method are also shown. The occurrence of TVM can be evaluated according to the outputs of the method, such as the design reasoning pattern, which is also presented in Section 4.

RQ1 asks, "what is the key individual and organizational knowledge needed in technology valuation to make the assumptions visible in order to support sustainability?" Knowledge gathering begins with targets for sustainability, which commonly originate from managers and are thus classified as individual knowledge. The knowledge about the targets should be collected and made visible to all participants after it is commonly accepted and can be used as organizational knowledge. After the targets are set, the knowledge related to the product is collected and modeled. This includes the properties and behaviors of the product, causing the targets to be defined first. The analogy to the target setting phase is obvious—the gathering of information starts with individuals and continues onto the organizational level. This makes possible the formation of a common understanding. Finally, the accounting data related to business contracts are considered when the valuation of technology is undertaken. The knowledge is based on EDR theories [15,18] and, more specifically, on research carried out in a technology evaluation context [32].

RQ2 asks, "how can the key individual and organizational knowledge be acquired?" To acquire the key knowledge, the proposed TVM includes six steps with specified tools and outputs. Proposed tools, such as the CSL and DRP, guide conversation in the workshops and support knowledge acquisition. The knowledge gathered is mainly tacit knowledge, and therefore the workshops are the main tools used for this purpose. It is preferable that this facilitation is undertaken according to the systems-based technocratic school and the spatial-based behavioral school described by [27], and that physical and mental space are used [28].

RQ3 asks, "how can this key individual and organizational knowledge be used in decision making?" Knowledge acquisition proceeds step by step in the TVM, and the acquired knowledge from the previous step is used to support the next step. Finally, when all the required knowledge has been acquired, modeled, and accepted, it can be used to support the technology decision. Individual tacit knowledge is transformed to individual explicit knowledge and group and organizational knowledge, according to [29]. In addition, according to [9], using the gathered knowledge supports the rational decision-making approach.

When evaluating the validity of the results, tacit knowledge is captured, modeled, and validated with the company personnel in the workshops. This is generally where the best available knowledge can be found. The main focus of this research is to support technology decision making for sustainability. The gathered knowledge is traceable, since the origin and rationale of the information is known and modeled. This approach enables an evaluation of the validity of the knowledge. Importantly, when information is documented and commonly accepted, the correction and improvement of knowledge also becomes possible, which supports the goal of sustainability. This method is also seen as beneficial for communication when evaluating the factual possibilities related to technologies [39] by using a pragmatic constructivist approach [40]. Product properties and behaviors are linked to all functions within companies and, therefore, TVM is seen as a tool for communication that can support knowledge acquisition.

The reliability and limitations of this research were evaluated from two perspectives. First, regarding the reliability of the proposed TVM, three case studies were undertaken; therefore, it is difficult to generalize the results, although the TVM was beneficial in all three case studies. This method relies heavily on workshops, and the know-how and capabilities of the facilitator or company personnel can affect the results. Additionally, the capabilities of company personnel to reach a joint understanding about the DRP model and dispositions can affect the reliability. Accordingly, it is possible that not all of the significant information was acquired, or that the DRP model is not fully valid. The proposed TVM is based on understanding the product properties and behavior to describe its dispositions. Therefore, if the product and technology being evaluated does not have these dispositions or the required knowledge is not available, this method cannot be used. Second, regarding the reliability of the research approach, case study research was selected, and therefore, the difficulties with generalization also exist in this perspective.

The proposed TVM can be used to achieve sustainability by supporting technology decisions. The knowledge acquired during the process relates to business and product modeling, which supports not only an understanding of technology, but also an understanding of the main elements that create potential benefits for the examined company. With this knowledge collected, it is possible to evaluate other actions to improve the performance of the company. It is recommended that future research test the proposed TVM in different contexts with different technologies to improve these tools so that they are easier to use.

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PUBLICATION V

Supporting technology decision-making in the manufacturing industry by improving the reliability of technology valuation

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Submitted