Open innovation for manufacturing technologies

– The operational technology management level perspective –

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List of Abbreviations

B2B	Business-to-Business
B2C	Business-to-Consumer
CEO	Chief Executive Officer
CIPP	Context, Input, Process, and Product
CS	Crowdsourcing
EHS	Environmental, Health and Safety
MRL	Manufacturing Readiness Level
OI	Open Innovation
TES	Technology Evaluation Score
TM	Technology Management
R&D	Research and Development
UIC	University-Industry Collaboration

Summary

This paper-based dissertation aims to contribute to the open innovation (OI) and technology management (TM) research fields by investigating their mechanisms, and potentials at the operational level. The dissertation connects the well-known concept of technology management with OI formats and applies these on specific manufacturing technologies within a clearly defined setting.

Technological breakthroughs force firms to continuously adapt and reinvent themselves. The pace of technological innovation and their impact on firms is constantly increasing due to more connected infrastructure and accessible resources (i.e. data, knowledge). Especially in the manufacturing sector it is one key element to leverage new technologies to stay competitive. These technological shifts call for new management practices.

TM supports firms with various tools to manage these shifts at different levels in the firm. It is a multifunctional and multidisciplinary field as it deals with all aspects of integrating technological issues into business decision-making and is directly relevant to a number of core business processes. Thus, it makes sense to utilize this theory and their practices as a foundation of this dissertation. However, considering the increasing complexity and number of technologies it is not sufficient anymore for firms to only rely on previous internal R&D and managerial practices. OI can expanse these practices by involving distributed innovation processes and accessing further external knowledge sources. This expansion can lead to an increasing innovation performance and thereby accelerate the time-to-market of technologies.

Research in this dissertation was based on the expectations that OI formats will support the R&D activities of manufacturing technologies on the operational level by providing access to resources, knowledge, and leading-edge technology. The dissertation represents uniqueness regarding the rich practical data sets (observations, internal documents, project reviews) drawn from a very large German high-tech firm. The researcher was embedded in an R&D unit within the operational TM department for manufacturing technologies. The analyses include 1.) an exploratory in-depth analysis of a crowdsourcing initiative to elaborate the impact on specific manufacturing technologies, 2.) a deductive approach for developing a technology evaluation score model to create a common understanding of the value of selected manufacturing technologies at the operational level, and 3.) an abductive reasoning approach in form of a longitudinal case study to derive important indicator for the in-process activities of science-based partnership university-industry collaboration format. Thereby, the dissertation contributed to research and practice 1.) linkages of TM and OI practices to assimilate

technologies at the operational level, 2.) insights about the impact of CS on manufacturing technologies and a related guideline to execute CS initiatives in this specific environment 3.) introduction of manufacturing readiness levels and further criteria into the TM and OI research field to support decision-makers in the firm in gaining a common understanding of the maturity of manufacturing technologies and, 4.) context-specific important indicators for science based university-industry collaboration projects and a holistic framework to connect TM with the university-industry collaboration approach

The findings of this dissertation illustrate that OI formats can support the acceleration of time-to-market of manufacturing technologies and further improve the technical requirements of the product by leveraging external capabilities. The conclusions and implications made are intended to foster further research and improve managerial practices to evolve TM into an open collaborative context with interconnectivities between all internal and external involved technologies, individuals and organizational levels.

1 Introduction

1.1 Situation

Technological breakthroughs in such disciplines as 3D printing, artificial intelligence and other frontiers of research and development will have a significant impact on the size and shape of the world's manufacturing and high-tech sectors and the firms that operate within them (PWC, 2016). The globalization of business enables firms today, to connect quickly with large global technical communities (Bogers et al., 2019). More and more work activities have become digitally connected, and new patterns of cross functional collaboration have emerged (Bogers et al., 2019). The rise of new technologies creates new competitive advantages and increases productivity across sectors and geographies (PWC, 2016). Furthermore, the pandemic has revealed that competitiveness of firms requires a more resilient and adaptable foundation to access assets on flexible terms within their organizations (PWC, 2016; Accenture, 2021). The positive impact on firms' performance of innovative managerial practices combined with R&D activities could support firms to manage these transformations (Nemlioglu & Mallick, 2017). Consequently, these recent developments lead to a necessity to further innovate managerial practices by combining strategical and operational management approaches.

Technology management (TM) includes both strategical and operational approaches (Asim & Sorooshian, 2019), which support firms to manage opportunities and risks of technologies. According to Gregory (1995), TM addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies needed to maintain a stream of products and services to the market. It focuses on "establishing and maintaining the linkages between technological resources and company objectives" (Phaal et al., 2004, p. 5). Consequently, it is a "multifunctional and multidisciplinary field" as it "deals with all aspects of integrating technological issues into business decision-making and is directly relevant to a number of core business processes including strategy, innovation, new product development and operations management" (Phaal et al., 2004, p. 2). Especially for technology intensive firms, creating competitive advantage is related to the capability of managing technological assets. Their TM capability is determined by the readiness and abilities of the firm to draft ideas and concepts and manage its development towards innovation. Thereby, a very crucial factor of this procedure is the time lag between the development of a technology and the commercialization of a product or service, and consequently correspondingly the evaluation and the planning of technologies (Abe, 2007).

TM routines are used in large firms to connect strategic (macro) and project (micro) levels of analysis (Burgelman, 1983). The routines were developed by Unsal & Cetindamar (2015) based on the TM models of Gregory (1995), Rush et al. (2007), Levin & Barnard (2008) and Cetindamar et al. (2009). The routines distinguish between TM activities and supporting activities and emphasis the increasingly important resource-based view, which define resources as source of sustainable strategic advantage of a firm (Collis, 1994Collis, 1994; Grant, 1996; Levitt and March, 1988). By managing and supporting R&D activities, technology management routines contribute to the firms' sustainable competitive advantage. (Skilbeck & Cruickshank, 1997; Unsal & Cetindamar, 2015).

The three core business processes of strategy, innovation and operations provide the necessary connections between TM processes and the wider business. In order to connect these three management theories in a technological perspective, it is necessary to start by defining a 'technological innovation'. Technological innovations are those innovations that embody inventions from engineering, applied sciences and/or pure sciences. An OECD study of 1991 captures the overall perspective of innovation as an iterative process initiated by the cognition of a new market and/or new service opportunity for a technology based invention. This process leads to new development, production, and marketing tasks striving for the commercial success of the invention itself. The innovation process comprises the technological development of an invention combined with its market introduction to end-users through adoption and diffusion.

In general, two types of innovation can be achieved – radical or disruptive innovation and incremental innovation. The radical innovation can be described as "a new product that incorporates a substantially different core technology and provides substantially higher customer benefits relative to previous products in the industry" (Chandy & Tellis, 2000, S.7, p. 7). The incremental innovation involves "relatively minor changes in technology and provide relatively low incremental customer benefits per dollar'' (Chandy & Tellis, 1998, p. 476). Incremental innovation is usually easier to achieve as it has likely a lower complexity and greater shared knowledge base (Cohen & Levinthal, 1990; Lane et al., 2006). All kind of innovation needs to overcome organizational innovation constraints, such as lack of freedom for innovative thinking, rejection of ideas and lack of support for innovation projects (Hölzle et al., 2018).

In order to address these constraints' technology is connected with the innovation process. Technology itself has been recognized as one of the major sources of competitive advantage (Edler et al., 2002; Liao, 2005; Phaal et al., 2006a). New technologies arise every day and firms need to be able to react fast and assess them (Teece et al., 1997) via appropriate reactions

(Levinthal, 1992). An appropriate reaction can be anticipating new (technological or market) opportunities and addressing these through new products, processes, or services (Teece, 2007). However, being aware of discontinuous technological change does not ensure that the firm will be able to produce adequate reactions (Paap & Katz, 2004; Lucas & Goh, 2009). TM provides firms with tools to execute these appropriate reactions at each organizational level.

One way to assess technology is through a 'hype cycle model' introduced by Gartner Inc. in 1995. This model explains a general path which technologies take over time, in terms of expectations or visibility of the value of the technology. The model proposes that technologies progress through successive stages that are pronounced by a peak, followed by a disappointment, and later a recovery of expectations (Fenn & Raskino, 2008). The current applied value of manufacturing technologies is fundamental for firms' competitiveness. Considering limited R&D resources and setup of a firm, this value enables the selection of superior technologies and thus assures the firms' competitiveness (Phaal et al., 2004). The hype cycle for manufacturing operations strategy, 2020 is illustrated in Figure 1-1. It exemplifies the connection of manufacturing technologies, their operations and supporting management practices (Gartner Inc., 2020).

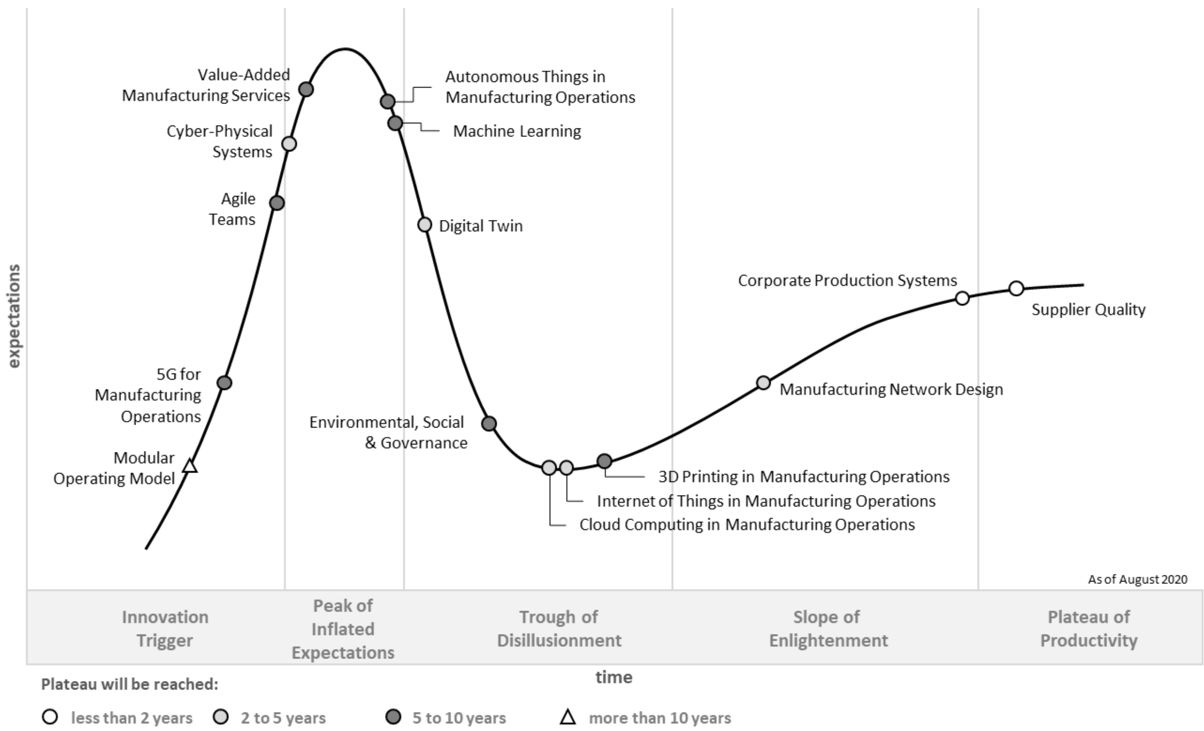

Figure 1-1: Hype Cycle for Manufacturing Operations Strategy, 2020 (Own illustration according to Gartner Inc., 2020)

Taking the digital twin as an example: "The digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin." (Tao et al., 2018) Hereby, the 'life' is the entire product lifecycle management, which is managed with various technological and managerial procedures. New technologies are promoting new paradigms such as internet of things and cyber physical systems. Such technologies enable passive machines to become active, endowed with intelligence, and able to make decisions. This technological shift calls for new organizational structures, new management practices and new decision-making structures that incorporate these technologies to improve firms' performance.

To link technology and innovation with operations management, it is essential to define 'production process': "A production process is the system of process equipment, work force, task specification, material inputs, work and information flows, and so forth that are employed to produce a product or service" (Utterback & Abernathy, 1975, p. 641). Once the production process has become standardized for product innovation, process innovation will evolve to improve the output productivity. The primary focus of 'process innovation' is the efficiency improvement of the production process for 'product innovation' (Utterback, 1996). This description illustrates that manufacturing technologies support product innovation. Thereby, it is worth to further investigate manufacturing technologies from an innovation and technology management perspective.

To assess manufacturing technologies, the OSD Manufacturing Technology Program (2016) developed the manufacturing readiness level. The method is used in the industrial environment with quantitative measures to assess the maturity of a manufacturing technology. In industrial environments, two main risk areas are immature product and manufacturing technologies. The manufacturing readiness level and technology readiness level collaborate with each other and are used to measure and point out those risks. A manufacturing readiness level for example always requires a nominal level of the technology readiness. The purpose of manufacturing readiness levels is to provide decision-makers with a common understanding of the relative maturity of the stages of manufacturing technologies, products, and processes (Bikramjit & Ghosh, 2017).The different levels of manufacturing readiness are illustrated in Appendix 1.

Each manufacturing technology must be developed, managed and set into operations to create a value for the firm. A major value is the firms' productivity, which is especially impacted by the escalating speed and power of information and communication technologies coupled with the increasing complexity of advanced manufacturing technologies (Shaw et al., 1997;

Oliner & Sichel, 2000). This leads to an increasing complexity and connectivity of product design and manufacturing processes (Esmaeilian et al., 2016; Mourtzis, 2020). Production processes and manufacturing system technologies are linked to the product context (Phaal et al., 2006b). They are the key drivers for cost reduction (Schuh et al., 2014) and process efficiency (Klocke et al., 2014) as well as product functionality improvement by enabling new product features.

To generate technological innovation, research focuses especially on two types of research and innovation models: 1. The traditional 'closed model' of innovation, which is based on autonomy: the company generates, develops and commercialises its own ideas (Chesbrough, 2003a) and 2. The 'Open Innovation' (OI) model (Chesbrough, 2003a), which involves distributed innovation processes (Coombs et al., 2003). In the OI model, firms develop a sense of external orientation (Tidd et al., 2006) and seek to commercialise both ideas originated internally as well as externally. Thus OI involves actively seeking and appraising external ideas, and avoiding the 'not invented here' syndrome (Katz & Allen, 1982, 1985). Important questions become who to access, and how (Tether & Tajar, 2008, S.1082). In the OI model a key challenge is to identify relevant new ideas developed externally, encouraging their production, and gaining access to them. Some of these external ideas can be found and accessed without establishing relationships (e.g., through searching the internet). Although it's more likely that some form of interaction will take place in such a way that both parties are aware of their involvement (Tether & Tajar, 2008, S.1082). The OI model is likely to remain pervasive as a component of R&D in large firms (Chesbrough & Brunswicker, 2014). Especially if the firm is active in an area of science and technology in which the government is making substantial investments through publicly funded programs, the firm has strong incentives to gain access to external knowledge. These firms can not rely solely on their own ideas and inhouse research but should also invite external sources to contribute. This is the outside-in branch of OI – also referred to as inbound OI (Chesbrough, 2003b).

First researchers demonstrated (Cassiman & Veugelers, 2006) that the expansion of previous internal R&D practices to further external knowledge sources can increase the innovation performance including the time-to-market of technologies. In general, the changing market conditions and international competitiveness push firms to shorten more and more their time-to-market targets (Prasad, 1997). Fast time-to-market capabilities allow firms to achieve a competitive advantage by higher market shares (Carpenter & Nakamoto, 1989), increased resource efficiency (Eisenhardt & Tabrizi, 1995), premium prices, and greater customer loyalty (Droge et al., 2000). Therefore, firms are increasingly reconsidering the fundamental ways in which they can reduce time-to-market of new products. Firms focus on customer centricity (Chen & Paulraj, 2004) as well as supplier integration to accelerate time-to-market (Petersen et al., 2005; van Echtelt et al., 2008). Chesbrough (2003a) found that suppliers are valuable by providing technical knowledge and specific capabilities, such as engineering, design, and manufacturing capabilities (Bozdogan et al., 1998; Narasimhan & Das, 1999). Furthermore, direct customer involvement can effectively decrease time-to-market of products (Leonard-Barton et al., 1994). Research implicates that earlier practices, which mainly focused on product costs, quality and time, are no longer enough to ensure competitive advantages (Evans et al., 2016)

1.2 Research field and theoretical foundation

In this dissertation, the discussion of OI for manufacturing technologies is embedded in the broader absorptive capacity research field and focuses at the operational level of TM. In the following, these theoretical perspectives are introduced.

1.2.1 Absorptive capacity

Cohen & Levinthal (1989, 1990) defined absorptive capacity as ''the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends'' (1990, p. 128). In this context, managers are challenged to put emphasis on absorptive capacity, which helps firms assimilate new technologies and processes. Already in 1993, Hall et al. showed that some firms were slow to assimilate flexible manufacturing technologies and thereby decreased their competitive advantage, which is reflected in a lower return on investment of these firms. In highly volatile environments, the lack of absorptive capacity can explain why firms are less effective at assimilating technologies and practices that lead to competitive advantage (Huber, 1996). Additionally, Lane & Lubatkin (1998) indicated that the ability to develop a sustainable competitive advantage depends on a firm's ability to convert knowledge into capabilities. The concept of dynamic capabilities approaches this necessary conversion. Dynamic capabilities are the organizational processes and routines to integrate, construct and reconfigure internal and external competencies to address the threat from a rapidly changing market environment (Teece et al., 1997; Eisenhardt & Martin, 2000). According to Teece (2007), dynamic capabilities are the firm's ability to respond to the dynamic of change by adapting, integrating and reconfiguring the firm's skills, resources and functional competencies. This is key to sustained profitable growth as the enterprise grows and as markets and technologies change. The concept utilizes the resource-based view that resources of the firm are valuable, rare and non-substitutable (Biedenbach, 2011; Peteraf et al., 2013) and become crucial to the firm's survival (Bowman & Ambrosini, 2003). Thereby, the innovation capabilities continuously transform knowledge and ideas into new products, processes and systems for the benefit of the firm and its stakeholders (Lawson & Samson, 2001, S.384). Merging absorptive capacity as a part of dynamic capabilities leads to view knowledge as a firm's resource (Zahra & George, 2002). Additionally important components of a firm's absorptive capacity are readily available relevant internal knowledge and communication networks (Tu et al., 2006, S.694). Dynamic capabilities impact firm's performance via the reconfiguration of the firm's operational competency. This "orchestration" process involves the modification, addition, divestment, and alignment of tangible and intangible assets. It requires shifting resources such as talent and money to where they will deliver the most value (Helfat & Peteraf, 2009).

1.2.2 Open innovation

In a recent paper of Bogers et al. (2019) the technology development is linked to a dynamic capabilities perspective as an approach to better strategically manage OI. Thereby, they created an initial framework, which should provide insights into when to use and when not to use OI. Other papers addressed further aspects of the dynamic capabilities perspective on OI in differing contexts on the strategic management level (Lee et al., 2019). Firms and academia evidently started to investigate OI practices at the strategic level (Kirschbaum, 2005; Laursen & Salter, 2006; Chesbrough & Brunswicker, 2013; 2014). Case studies, which are particularly powerful in exploring a phenomenon in its context while retaining the richness of the studied case and its context (Eisenhardt & Graebner, 2007), are published and highlight OI instruments such as outsourcing R&D, technology in-sourcing (Chesbrough, 2003b, 2006), user integration (Piller & Walcher, 2006) and the integration of OI in an entire firm (Rohrbeck et al., 2009). The utilization of OI methods has increased substantially over the last years (Howells, 2008; Enkel et al., 2009; Gassmann et al., 2010; Bogers et al., 2017). The field has moved beyond the bilateral collaborations of Chesbrough (2003b) to various network typologies of collaboration (West et al., 2006) and ecosystems (West & Bogers, 2014). Research has mainly focused on such networks in the business-to-consumer (B2C) markets like computing and communications industries where these forms are common (West & Bogers, 2016). Advanced research looks at understanding the underlying motivation of firms engaging in OI and how individuals influence the OI process (Henkel, 2006; Afuah & Tucci, 2012; Poetz & Schreier, 2012). Quantitative research results show evidence that even companies outside high-tech industries are adopting OI methods (Chesbrough & Crowther, 2006; Lichtenthaler, 2008). Thus, the business-to-business (B2B) market (i.e., manufacturing industry) is worth to further investigate from an OI perspective.

Du et al. (2014) responded to the call of West et al. (2006) to analyse OI at the operational level of R&D projects and not at the firm level, and analysed 489 R&D projects of a large R&D intensive European manufacturing firm. They distinguished between two types of OI partnerships – science-based partnerships (universities and knowledge institutions) and market-based partnerships (customers and suppliers). Further quantitative studies examined the relationship between OI and performance at the R&D project level (Cassiman et al., 2009, 2010; Salge et al., 2013) and the adoption of OI at the project level (Brunswicker & Chesbrough, 2018). All these quantitative studies are mainly focusing on the inputs and outcome measures at the R&D project level as well as the overarching formats of OI, but not at the operational management of these projects. Particularly, there is a lack of concepts and indicators for the development, exploitation as well as evaluation of technologies with OI procedures at the operational level (Lichtenthaler, 2008; Rubera et al., 2016). There is great promise in further exploring the more detailed mechanisms of OI. Thus, OI requires new management approaches and profound capabilities in technology “integration”. (Bogers et al., 2019). More and more commitments inside a firm to OI will dramatically expand the number of technology partners one has to evaluate and work with. This research gap is addressed by this dissertation at the operational level with two different OI formats.

A very promising OI format of science-based partnership is UIC. University–industry collaboration is one of the collaboration practices in which knowledge and resources are transferred between parties. UIC is a promising tool for enhancing organizational capacity - where an organization employs external networks (Dess & Shaw, 2001), a complementary option to traditional internal R&D (Coombs et al., 2003). The UIC can be utilized to leverage the competitive advantages of the engaged firms based on a complementary resource approach (Das & Teng, 2000). In this format, the firm actively seeks and appraises external ideas to commercialise them in these activities. Perkmann et al. (2011)) stated that these activities may be managed “in a manner similar to the firm’s mainstream R&D activities, including using creativity techniques for ideas’ generation, ranking and stage-gate processes for project selection and continuation, portfolio analysis and other tools“ (2011, p. 212). These mainstream activities are also the basis for OI procedures. Most innovation research, which deals with innovation in terms of technology and R&D, focuses on the outcomes of innovation (Crossan & Apaydin, 2010) rather than on the in-process activities of UIC. Compared to traditional R&D projects, UIC R&D endeavours involve sometimes more stakeholders, implicate complex project arrangements, may have special rules regarding documentation, and financing as well as a lack in experienced partners (Wang et al., 2017). Due to firm resources invested in such collaborations and the difficulties involved in bringing them to successful conclusion, the procedures put in place to manage them are a subject worthy of investigation (Rybnicek & Königsgruber, 2019). There is the demand to investigate the challenges encountered by firms in setting up and managing performance management systems in university–industry collaboration. Qualitative research based on case studies are required to analyse the interorganizational governance mechanisms in university–industry collaborations (Bstieler et al., 2015, S.119). The evaluation of the outcome of technology translation in university–industry collaboration formats are generally executed by industry or universities actors who might have determined the outcomes by comparison to prior needs and expectations. The definition of the success of the interaction and its outcomes may vary between these actors (Barnes et al., 2002). Therefore, there is a need to investigate other alternatives to more objectively measure the effectiveness of university–industry collaboration, in addition to the subjective measure currently employed (Ankrah & AL-Tabbaa, 2015, S.401). The intellectual discourse and the fresh perspective of academic collaborators (resulting from their consistent interaction with state-of-the-art knowledge) can contribute to the R&D capabilities of a firm, perhaps also replacing these capabilities. Valid research outcome in this direction can impact the decision making regarding the investment in university–industry collaboration (Ankrah & AL-Tabbaa, 2015, S.402). Therefore, there is a need for longitudinal research to provide additional insights into cause-and-effect dynamics and help in assessing the 'value' of the full range of outcomes in both short term and long-term scales. Although the importance of university–industry collaboration through evaluation has been acknowledged by scholars (Seppo & Lilles, 2012; Rossi & Rosli, 2015). A universal set of indicators does not exist and the need for developing such a set is highlighted by existing studies (Perkmann et al., 2011; Piva & Rossi-Lamastra, 2013). This deficit represents a serious research gap that the dissertation addresses.

Another OI activity is CS, stated as "the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call" (Howe, 2006). It offers firms the opportunity to outsource the development of solutions of their innovation problems to external problem solvers, thus saving resources and time (Tapscott & Williams, 2010; Terwiesch & Xu, 2008). CS enables the acceleration of new ideas (Poetz & Schreier, 2012). To leverage ideas and knowledge, these ideas need to be included in the internal R&D processes of a firm. As mentioned, CS allows to broadcast topics to external individuals to perform problem solving processes and thereby reduce the solution development time, costs, and risks (Afuah & Tucci, 2012; Bayus, 2013; Jeppesen & Lakhani, 2010). Many studies have researched several factors in the implementation and execution of CS like motivation of the crowd (Kosonen et al., 2013; Ståhlbröst & Bergvall-Kåreborn, 2011), skills related to the CS process itself (Malhotra & Majchrzak, 2014) and the selection and classification of ideas (Hoornaert et al., 2017). The final assessment of the impact related to the problem-solving performance, such as the quality of the best solutions retrieved and the development time of these solutions (Afuah & Tucci, 2012; Atuahene-Gima, 2003), is handled in very few studies. A challenge is to design an effective method for validating the CS process and incorporating the generated ideas into the firm processes. Tasks like examining the idea content or crowd feedback can help the firm to define the probability of implementation during the crowdsourcing process (Hoornaert et al., 2017). Ideas alone are not worth much if not executed well. According to Whitla (2009) firms utilize CS in the areas of product development, advertising and promotion as well as marketing research. Other researchers have looked at CS in functions like product development and configuration, product design, competitive bids, permanent open calls, community reporting, product rating, and customer-to-customer support (Kleemann et al., 2008). The manufacturing area has not been considered yet by research reviews to the knowledge of the others. This dissertation addresses this research gaps by evaluating a manufacturing-related CS initiative.

Frameworks of university–industry collaboration and CS are mostly derived from a synthesis of the theoretical literature, future research should attempt to validate it empirically (Perkmann et al., 2011, S.214).

1.2.3 Technology management

TM consists out of three levels – corporate (network view), business (external view), and operational (internal view) (Skilbeck & Cruickshank, 1997). "Corporate" is concerned with the multi business activities in respect to the world market (Perrino & Tipping, 1989). "Business" links the technological activities and market focus to ensure competitive advantages of the firm. It includes portfolio, strategy, acquisition and R&D management (Phaal et al., 2006a). In this area, several tools were developed to manage technologies (Betz, 1993; Steele, 1989). A management tool is thereby according to Brady et al. (1997) "a document, framework, procedure, system or method that enables a company to achieve or clarify an objective" (1997, p. 418). Sophisticated tools at this strategic level are for example technology forecasting (e.g. trend extrapolation, S-curves (Rohrbeck, 2007)), road mapping (e.g. selection of technology fields, timing of technology development initiatives (Phaal et al., 2006b)), and technology protection (intellectual property (Ernst, 2003)). The "Operational" addresses the internal R&D and innovation management of the business (Twiss, 1992). It describes how to optimise internal processes to manage technology effectively. This field is mainly defined by R&D management and operational management procedures. The operations management is the "selection and management of transformation processes that create value" (Lovejoy, 1998, p. 106). In an cluster analysis Unsal & Cetindamar (2015) elaborated three clusters of TM activities. The first cluster is the technology development cluster. The enclosed processes are mainly the technology identification, the technology selection and the acquisition processes. These are the main activities of the technology development, which is especially addressed in this dissertation. The second cluster is called technology exploitation and innovation cluster. In the exploitation activity the desired profit or other benefits can be generated inside the firm. The implementation, absorption and operation of the technologies are required to lift these benefits. Thus, to create innovations inside firm, technologies must be developed and deployed in the specific firm setup. The last cluster is the project management cluster. At the operational TM level, technologies are internally identified, selected, and an acquisition strategy defined (Probert et al., 2000).

1.2.4 Manufacturing technologies

As described in the previous section, manufacturers require to adapt and to open up to in other industries well known and proven research and innovation procedures (e.g., computing and communications industries (Rohrbeck et al., 2009) or life science industry (Kirschbaum, 2005)). Manufacturers need to innovate on a constant basis to stay competitive (Kumar & Motwani, 1995). Their success significantly depends on the efficiency and productivity of manufacturing processes (Holweg, 2007; Klocke et al., 2014). Their assets as resources, machines and know-how are deriving the two factors of efficiency and productivity (Schuh et al., 2014). Manufacturers need to increase the time-to-market of manufacturing technologies to stay competitive in a global market (Driva et al., 2000). Large manufacturers have embraced lean management approaches at the operational level (Bhasin, 2012). Each manufacturing step is analysed and optimized with specific tools per manufacturing area. Quality management contains new technologies like 3D scanning, X-Ray etc. with worldwide defined standardization. Casting processes are fully simulated, and 3D printing technologies allow more complex product geometries and flexible on-site production capabilities. Technology is scouted and roadmaps are created on the strategic TM level. Procedures are in place on how to sense and select these technologies per firm (Teece, 2007). However, only a few studies have been published on how to evaluate and manage the selected technologies on an operational level. Empirical research methods based on the TM model of Unsal & Cetindamar (2015) are required to validate TM models. The constant evaluation of identified and selected technologies over the entire technology lifecycle, including events like stage gates or technology roadmap planning, supports the firm in its decision-making processes. It is important for a manufacturer to focus its available R&D resources on the most promising technologies. Evaluation models to assess technologies concentrate on different production outputs for demands and order winning criteria on the strategic TM level (Miltenburg, 2005). Environmental issues play a major part in strategic manufacturing decisions (Azzone & Noci, 1998; Pun et al., 2002). Research has shown, that being environmentally proactive can produce competitive gains (Hart, 1995; Ahmed et al., 1998; Klassen & Whybark, 1999). Earlier empirical studies often used general firm-level financial outcome measures, such as revenues or profitability, for the organizational environmental practices (Ahmed et al., 1998; Klassen & Whybark, 1999). Especially at the operations level, these measures provide limited value as practitioners make decisions about environmental and competitive demands without these firm-level financial outcomes. There is no holistic evaluation model at the operational TM level, which considers environmental criteria. Furthermore, social effects, e.g. employment rate changes or other societal impacts, are lacking due to their usual reflection in the macroeconomic contexts but not at the microeconomic level of a firm (Brandenburg et al., 2014). There is therefore a need to provide models with these important criteria at the operational TM level. Increasing complexity of manufacturing (ElMaraghy et al., 2012) and challenges in the implementation process like investment justification process, decision and analysis process, lack of knowledge (García A & Alvarado I, 2013) are calling for a more industry-related evaluation model. Concluding, this dissertation empirically analyses data sets of manufacturing technologies at the operational TM level.

Obradović et al. (2021) argued that it is promising to apply an OI perspective to accelerate the time-to-market of manufacturing technologies. Though, it is unclear how OI can facilitate and accelerate the development and exploitation of manufacturing technologies and what are the important indicators in this emerging field of research (Travaglioni et al., 2020; Obradović et al., 2021). The dissertation examines for manufacturing technologies particular OI cases at the operational TM level in order to provide insights into in-process guidelines for projects teams.

To create a profound starting point and establish a point of scientific origin, the dissertation connects the well-known concept of TM with OI formats and applies these on specific manufacturing technologies within a clearly defined setting.

Consequently, the following overriding questions can be deduced to address these knowledge and research-practice gaps: **How do OI formats impact the R&D activities of manufacturing technologies at the operational TM level?**

Thereby, the following sub-questions guided the dissertation:

- *How does CS accelerate the R&D of manufacturing technologies at the operational level?*
- *How can firms successfully define the value of selected manufacturing technologies at the operational TM level?*
- *What are important indicators in an UIC of R&D manufacturing technologies at the operational TM level of the firm?*

Considering these questions, the overall goal of the dissertation is to create a new perspective and insights on OI formats for manufacturing technologies. Accordingly, there are three especially practical subgoals: (1) to analyze how fast external valuable ideas for a manufacturer progress with a specific OI format and support the operational level of the firm; (2) to define an evaluation score model for manufacturing technologies, which focuses at the operational level of a firm and supports the decision making; and (3) to create empirical evidence from application of a modern research set-up in order to deliver important indicators and understanding of UIC mechanisms through long term observation within a clearly defined setting. The research goals are dedicated on exploration and understanding and are thus qualitative instead of quantitative in nature.

1.3 Procedure and article summary

This dissertation aims to contribute to the understanding of the connection of OI and operational TM procedures for manufacturing technologies. The structure and procedure of the dissertation is illustrated in Figure 1-2. The following paragraphs describe the empirical environment and the research activities of the dissertation.

The dissertation focuses on specific OI formats for manufacturing technologies at the operational TM level in an R&D unit. This unit is part of the Siemens' Gas Turbine Manufacturing Network producing heavy-duty gas turbines for stationary power generation with a power output of up to 593 MW. In a gas turbine power plant, after power output, the main technical requirements are lifecycle cost, efficiency, and environmental compatibility. As in all combustion engines, higher combustion temperatures result in higher efficiency and lower emissions from the gas turbine. The advanced manufacturing technologies as well as intensive R&D activities aim to achieve these requirements. Technological improvement regarding the overall product often goes hand-in-hand with innovation in the manufacturing processes. The manufacturing technologies applied in gas turbine manufacturing can be compared with those applied in aero-engine manufacturing. These manufacturing technologies reach a high technological level paired with a high degree of specialisation; thus, they are not commonly available. On one hand, most of the technologies need high capital investments in machine tools and equipment. Similarly to aircraft manufacturing, all process modifications must be certified. Together with the complexity of technology development, this results in high time effort for implementation. On the other hand, because of the dedicated materials and quality requirements, there is a high technological risk in all process modifications. The R&D unit is responsible for innovative manufacturing and digitalization technologies in the entire manufacturing network. The Berlin gas turbine plant consists of five manufacturing units (e.g. machining of large parts, blades and vanes manufacturing). Each manufacturing unit is organised as a strategically independent business segment with a clearly defined field of activity. The units follow the strategy of using technological improvements as well as standardisation to ensure their competitiveness. TM procedures are used at the operational level to establish a direct linkage between the existing technological competencies in the manufacturing units and the responsibility for technological improvements in the R&D unit.

The following articles display a logical, structural relationship and each relate to specific phases of the TM process.

The dissertation starts with a first article which outlines an empirical approach by analysing an exploratory, in-depth pilot case study of a crowdsourcing (CS) initiative. This initiative concentrates on the fuzzy-front end of the innovation funnel in combination with the technology planning phase of manufacturing technologies. OI formats like CS can generate new ideas for process innovation, access external knowledge and speed up the innovation process from several months onto days (Tapscott & Williams, 2010; Terwiesch & Xu, 2008; Lakhani, 2008; Poetz & Schreier, 2012). The main applications of CS in firms are found in the product development, promotion, and marketing research but not in manufacturing (Kleemann et al., 2008; Whitla, 2009). Each CS initiative has unique conditions and own goals. Comparability and efficiency are hard to accomplish and so far, there is no joint evaluation approach available (Evans et al., 2016). Thus, the purpose of this first article is to investigate how CS can accelerate time-to-market of manufacturing technologies in a business-to-business (B2B) environment. Therefore, a single in-depth exploratory CS pilot study was conducted using a mixed-method approach. The article outlines a corporate CS initiative with three CS phases (idea generation, refinement, prototyping) as well as the subsequent development and implementation phases. In this initiative, several business units of one large international firm plus eight universities worldwide worked together over a period of seven months.

Chapter	Introduction	*Article 1:* Crowdsourcing for manufacturing technologies	*Article 2:* Technology evaluation score model	*Article 3:* University-industry collaboration indicators	Synthesis
Objective	Introduction of research objective and outline of present work	Open innovation format to analyze the fuzzy-front end and technology planning	Model to evaluate selected technologies over the entire technology management process	Open innovation format to analyze important indicators for the technology development and exploitation	Main results, contribution, and conclusion, critical reflection, outlook for further research
Methodology	-	Exploratory in-depth pilot case study	Deductive approach - Sensitivity analysis	Longitudinal case study - Abductive reasoning approach	-
Data	-	Observations, internal documents, internal project reviews	Observations, internal documents, internal project reviews	Observations, interviews (n=25), internal documents, internal project reviews	Internal documents, ERP data sets
Key findings	• Firms need to embrace technological breakthroughs to stay competitive • Traditional R&D approaches and managerial practices are not sufficient anymore • Knowledge about the value of manufacturing technologies is crucial for the productivity and efficiency of the firm • External sources need to be assimilated and applied at the operational level • Application of OI formats at the operational TM is purposed for manufacturing technology innovation	• External knowledge can be used to develop ideas into real manufacturing processes - the implementation depends on resources, internal management support • CS can accelerate the time-to-market of manufacturing technologies • Basic evaluation guideline to assess the cost, quality and time impact of CS and compare initiatives (constant evaluation leads to systematic improvements of crowdsourcing)	• Industry-related evaluation models at the operational level of TM • Consideration of social and environmental criteria to access the technology on the microeconomic level → new shifts in the importance of manufacturing technologies • Support problem solving in the investment justification process, decision and analysis process, and knowledge management	• Framework to connect UIC R&D projects with the operational technology management level • Mechanisms had to be in place during the development process to keep the progress and to justify the efforts and expenses of the activity inside the firm • Progress of the technologies is causally linked with indicators like adequate resources, teamwork, training, roles, re-baselining, applied research, access to leading edge technology and clear hand overs etc.	• Despite extensive data basis, present work comes with known limitations due to explorative case-study approach. • Validation of findings and models with further cases and broader data basis required. • Further promising research pathway are in particularly: - Multi-level landscape of OI and the interdependencies with TM - In-process activities in OI formats for manufacturing technologies - Linkage of disruptive technologies with OI and TM procedures
Technology management phase	-	Technology forecasting and planning	Technology evaluation	Technology development and exploitation	-
Publications	Dissertation	Dreßen, S., Hoelzle, K., Neuenhahn, T. & Weinreich, I. (2018). **Crowdsourcing for manufacturing technologies - Acceleration of time-to-market**. In 25th Innovation and Product Development Management Conference (IPDMC). Porto, Portugal.	Dreßen, S., Solis, L. E. & Neuenhahn, T. (2018). **Development of a Technology Evaluation Score Model for Manufacturing Technologies**. In 25th International EurOMA Conference. Budapest, Hungary.	Dreßen, S. (2020). **University-Industry Collaboration Indicators for Manufacturing Technology R&D Projects – The Industrial Perspective**. In 27th Innovation and Product Development Management Conference (IPDMC). Antwerpen, Belgium.	Dissertation

Figure 1-2: Structure and overview of the dissertation (Own illustration)

To better understand the acceleration of the manufacturing technology development and the implementation of the ideas, a CS evaluation methodology was developed by combining the CS process with the Context, Input, Process, and Product (CIPP) model (Stufflebeam, 2007). The methodology is a first attempt to evaluate CS and herewith make its effort and value transparent and comparable inside the firm. The data clearly shows that the outcomes of the initiative vary significantly in terms of their readiness and ability to accelerate the time-to-market in the manufacturing area. Some of the ideas exceeded the expectations of the corporate partner. Other ideas failed to be implemented. The developed methodology provides a clear guideline to evaluate the entire initiative. The findings also show that CS is in fact useful and applicable in the business-to-business (B2B) manufacturing sector and could be a new way to improve time-to-market. Furthermore, CS can lead to more innovation and increase resource efficiency.

To measure the value of the created ideas and prototypes at the operational TM level, the second article of the dissertation focusses on how firms can successfully define the value of selected manufacturing technologies. The steady evaluation of a manufacturing technology is essential for the resource allocation and scouting activities of a firm (Dietrich & Cudney, 2011). Leveraging new manufacturing technologies is one key element for producing firms to stay competitive. The complexity and number of technologies as well as their influence factors (e.g. market, environment, and society) are increasing every day. Firms require tools to leverage these manufacturing technologies based on their current situation (Schuh & Kramer, 2016). The researcher had access to internal documents, observed discussions about the value of specific technologies, and participated in internal project reviews. A deductive approach was used to prove the assumption to increase the competitive advantage of firms by evaluating technologies at the operational TM level. To create the model inside the firm, the gathered data was summarized and, in several discussions with the project leaders, the model was elaborated. A sensitivity analysis was executed to assess the impact of the weighting factors as well as the partial scores. The sensitivity analysis indicated that the impact rate constantly dropped and then stayed constant. A standard deviation was calculated to generate high consistency. This data revealed that the model generates consistent distributed scores. Due to the complexity in technologies, none of the considered technologies can reach a score of hundred percentages of all evaluated criteria. The model allows an internal customization of the criteria. It helps to constantly manage the technology projects and is adaptable to the requirements of the firm. Furthermore, the model reacts to market changes and governmental regulations, and thereby generates a competitive advantage for the firm. To leverage these advantages, the R&D expenses have to relate to the evaluation outputs in the firm. The developed technology evaluation score (TES) model enables firms to evaluate selected manufacturing technologies at the operational TM level in a standardized way. It considers business, environmental, and social aspects. After the evaluation, the technologies are prioritized and thereby enable a competitive advantage.

Once the firm sensed the value of a certain technology, the firm must acquire and implement it to leverage its potentials. OI is a new management approach, which provides profound capabilities in that kind of technology "integration" (Bogers et al., 2019). Thus, the third article concentrates on the technology development and exploitation phase of manufacturing technologies with the help of the OI format: University-industry collaboration (UIC). The article elaborates important indicators to succeed in a UIC of R&D manufacturing technologies at the operational TM level of the firm. To derive these indicators, a qualitative longitudinal case study was conducted using an abductive reasoning approach. In the abductive reasoning approach researchers can expand their understanding of theory and empirical data by constantly going "back and forth" (Dubois & Gadde, 2002). The researcher observed five UIC manufacturing technology R&D projects between a German university and German large high-tech firm over a period of two years. All projects were executed with the same amount of budget. Also in this third article, the main driver to analyse the OI formats was the constant need of the firm to reduce time-to-market (Petersen et al., 2005; van Echtelt et al., 2008) due to constantly changing global market conditions and international competitiveness. The field of UIC is a promising one for enhancing organizational capacity, as a complementary option to traditional in-ternal R&D (Dess & Shaw, 2001; Coombs et al., 2003). It can be utilized in leveraging the competitive advantages of the engaged firms (Das & Teng, 2000). Advanced manufacturing technologies, equipment or methodology that is part of the production system for improving performance, are key drivers for cost reduction and process efficiency as well as product functionality improvement (Schuh et al., 2014; Klocke et al., 2014). Not only at the strategic level, but also at the operational level, the assessment and selection of manufacturing technologies is crucial to assure the competitiveness of a firm. UIC enables the essential access of a firm to leading edge technologies and to new knowledge expertise in order to foster innovation and stay competitive (Caloghirou et al., 2001; Schartinger et al., 2001; Santoro & Chakrabarti, 2002; Tether, 2002; Bayona Sáez et al., 2002; Cassiman & Veugelers, 2006). However, although research has devoted considerable efforts to find essential indicators for the success of UIC, so far TM procedures are not contextualized in specific UIC formats. Thus, the purpose of this article is to investigate important UIC indicators for manufacturing technology R&D projects in order to leverage the potential of UIC at the operational TM level. To better understand the interactions of UIC in R&D projects within a firm, a framework was developed connecting UIC lifecycle stages with TM procedure. This framework was used to empirically validate already developed indicators and categorize new influencing indicators of the in-process activities stage of UIC. The applied methodology is a first attempt to elaborate context-specific indicators for manufacturing technology UIC in R&D projects. It clearly addresses the criticism that research is too exclusively orientated towards the outputs (Rossi & Rosli, 2015) and the need to apply case specific metrics. Via the qualitative approach, existing theories and indicators were validated within the case study such as geographic proximity, product testing with independent credibility in testing or with mutually agreed project plans.

After this introduction the main dissertation papers are presented. Finally, the dissertation concludes by 1.) summarizing the main results, contribution, and conclusion, 2.) discussing the practical, theoretical implications and limitations of this dissertation, and 3.) providing an outlook as well as future research pathways.

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2 Crowdsourcing for manufacturing technologies – Acceleration of time-to-market

2.1 Introduction

Manufacturing technologies are key drivers for cost reduction (Schuh et al., 2014) and process efficiency (Klocke et al., 2014). Firms are facing a multitude of challenges when assessing and implementing advanced manufacturing technologies, defined as any equipment or methodology that is part of the production system for improving performance (Chuu, 2009). One challenge is the frequent and rapid emerging of new technologies pushing firm1s to innovate in order to sustain their competitive position (Akman & Yilmaz, 2008). Evans et al. (2016) stated that earlier practices such as focusing on product costs, quality and time are no longer enough to ensure competitive advantages in the manufacturing industry. Consequently, the assessment and selection of manufacturing technologies for that particular firm is crucial in order to assure the competitiveness of a company (Phaal et al., 2004). A second challenge is innovation speed. Open innovation (OI) allows knowledge to enter and exit the firm and therefore improves the access to innovation (Chesbrough, 2003). Lakhani (2008) found in a case study that the integration of experts outside the industry can accelerate the innovation process from several months to days (Lakhani, 2008). Crowdsourcing (CS) is a form of "outside-in" collaboration in Chesbrough & Crowther (2006) sense. CS outsources internal tasks to a large number of participants in the form of an open call. Organizations are looking for ideas building on the knowledge and expertise of the crowd instead of depending on a limited number of specified experts (Howe, 2006). The variety of CS initiatives is broad and there are many examples in the consumer business domain (Brabham, 2008), e.g., involve customers to participate in brand-related activities (Howe, 2008; Parent et al., 2011). Thereby, CS enables the acceleration of new ideas (Poetz & Schreier, 2012). In the business-to-business (B2B) area, the value of CS is still developing (Simula & Vouri, 2012). Only a few initiatives have so far addressed the topic in this context (Kärkkäinen et al., 2012; Simula et al., 2015). An evaluation of CS research shows three current research foci: conceptualization, system, and application (Zhao & Zhu, 2014). Conceptualization aims to explore what CS is, how it works, and how it is different from related concepts. System research analyzes the set of components and their formed structure. CS are individual systems containing multiple views such as planning, requirement, design, implementation, deployment, operational, and behaviour, etc. Application researches the situation and purposes of CS. It can be viewed as a paradigm (Albors et al., 2008; Brabham, 2008; Kazman & Chen, 2009; Vukovic et al., 2010), a process (Stewart et al., 2009; Whitla, 2009), or a platform (Kittur et al., 2008; Schenk & Guittard, 2011; Vukovic, 2009).

In this study, we focus on the application part. According to Whitla (2009) firms utilize CS in the areas of product development, advertising and promotion as well as marketing research. Other researchers have looked at CS in functions like product development and configuration, product design, competitive bids, permanent open calls, community reporting, product rating, and customer-to-customer support (Kleemann et al., 2008). The manufacturing area has not been considered yet by research reviews to the knowledge of the others. We address this gap by evaluating a manufacturing-related CS initiative. The paper illustrates an evaluation approach for CS applications and presents a first glance of how CS can accelerate the development and implementation (time-to-market) of manufacturing technologies. Based on a CS initiative in the B2B environment, we develop our evaluation model, test it and look at the implementation of the model.

The next section provides the theoretical background of this study. Afterwards, the research method and CS initiative are described. The empirical findings illustrate how the evaluation methodology can be applied with this initiative and based on specific criteria how CS accelerates time-to-market. Finally, theoretical and managerial contributions are presented together with suggestions for future research.

2.2 Theoretical Background

2.2.1 Crowdsourcing applications

Howe (2006) popularized the term “crowdsourcing” and defines it as “the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call (Howe, 2006)”. As a form of user-driven innovation and co-creation, CS is a way to access the intelligence distributed among a crowd (Chanal & Caron, 2008; Schenk & Guittard, 2011). It offers firms the opportunity to outsource the development of solutions of their innovation problems to external problem solvers, thus saving resources and time (Tapscott & Williams, 2010; Terwiesch & Xu, 2008). There are different research foci in the field of CS. The CS system, the set of components and their formed structure (Zhao & Zhu, 2014), in this study is the CS process of Gassmann defined based on long-term experience in the field of OI for technology management (TM) at the University of St. Gallen as well as in-depth analysis of CS projects (Muhdi et al., 2011). It includes the preparation, initiation, development, evaluation and use phase. Simula & Ahola (2014) reviewed initiatives of industrial firms and identified four distinct configurations of innovation CS - the internal, community, open and broker CS (Simula & Ahola, 2014). In each of these configurations, the contributors provide the firms with ideas for specific topics. The initiative can be routine, content and inventive initiatives (Pénin & Burger-Helmchen, 2011), as well as selective or integrative operations (Schenk & Guittard, 2011). Integrative CS aims to generate a high amount of data or information. Single elements have no value, but the amount of the complementary data generates the value for the firm. In the selective CS a specific need is addressed, and the data is selected by the firm (Schenk & Guittard, 2011).

This study focuses on the selective CS with a community configuration, where the firm receives a set of possible solutions from the crowd and then selects the solution that seems most appropriate. The amount of these initiatives is increasing in the industry, in which firms open their internal innovation funnel to include external knowledge (Tucci et al., 2016). CS allows to broadcast topics to external individuals to perform problem solving processes and thereby reduce the solution development time, costs, and risks (Afuah & Tucci, 2012; Bayus, 2013; Jeppesen & Lakhani, 2010). Many studies have researched several factors in the implementation and execution of CS like motivation of the crowd (Kosonen et al., 2013; Ståhlbröst & Bergvall-Kåreborn, 2011), skills related to the CS process itself (Malhotra & Majchrzak, 2014), and the selection and classification of ideas (Hoornaert et al., 2017). The final assessment of the impact related to the problem-solving performance, such as the quality of the best solutions retrieved and its speed, namely its development time (Afuah & Tucci, 2012; Atuahene-Gima, 2003) is handled in very few studies. However, the firms need to validate the integrity, and/or data quality of the input, to demonstrate the value of the innovation. A challenge is to design an effective method for validating the CS process and incorporate the generated ideas into the firm processes. During the CS process tasks, like examining the idea content or crowd feedback, can help the firm to define the probability of implementation (Hoornaert et al., 2017).

2.2.2 Manufacturing technologies and their time-to-market

Production companies need manufacturing technologies for producing current and future products. The changing market conditions (such as fluctuating production load, and disruptive innovation allowing new product features as enabled e.g. by additive manufacturing), and international competitiveness lead to shorter time-to-market targets (Prasad, 1997). Fast time-to-market capabilities allow firms to achieve a competitive advantage by higher market shares (Carpenter & Nakamoto, 1989), increased resource efficiency (Eisenhardt & Tabrizi, 1995), premium prices, and greater customer loyalty (Droge et al., 2000). Therefore, firms are increasingly reconsidering the fundamental ways in which they can reduce time-to-market of new products. They focus on customer (Chen & Paulraj, 2004) as well as supplier integration to accelerate time-to-market (Petersen et al., 2005; van Echtelt et al., 2008). Chesbrough found that suppliers are valuable sources (Chesbrough, 2003) by providing technical knowledge and specific capabilities, such as engineering, design, and manufacturing capabilities (Bozdogan et al., 1998; Narasimhan & Das, 1999). The customer involvement effectively decreases time-to-market (Leonard-Barton et al., 1994). Cassiman & Veugelers (2006) highlighted that external knowledge only increases the innovation performance of manufacturing firms when the firm is simultaneously engaged in internal R&D activities. New technologies arise every day and companies need to be able to react fast and assess them (Teece et al., 1997). They must be evaluated, adopted and routinized in the firm (Zhu et al., 2006) to lift the potential acceleration of time-to-market. From the manufacturing perspective, the firm needs to establish production processes, prepare facilities for production ramp up, and improve manufacturing yields for profitability prior to market entry of the product. The firm improves manufacturing yields through better manufacturing process design by building prototypes, testing them, checking performance, and preparing the facilities for the qualification and production process. These procedures of the manufacturing technologies are all capabilities to accelerate the time-to-market of new products. In this study we use CS to access the external knowledge for manufacturing technology improvements in internal R&D activities. Accelerating the manufacturing technology development and implementation implicates to accelerate the time-to-market.

2.2.3 Maturity assessment of manufacturing technologies

The Manufacturing Readiness Level (MRL) is a procedure developed by the United States Department of Defense in 2005. It is a method used in the industrial environment with quantitative measures to assess the maturity of a manufacturing technology. The two main risk areas are immature product and manufacturing technologies. The technology readiness level (TRL) and the MRL, which are used to measure and point out those risks, collaborate with each other. An MRL for example always requires a nominal level of the technology readiness. There are ten MRLs which correlate to the nine TRLs. MRL 1 to 3 are attached as a group in Conceptualization, MRL 4 to 6 together as Technology Development and MRL 7 to 10 collectively in the Development and Product Deployment (OSD Manufacturing Technology Program, 2016). A project can be assessed for a MRL when doing a MRL review process. For a correct assessment, MRL criteria and categories have been defined by the OSD Manufacturing Technology program. The categories are as follows: 1. Technical - Primary Technical Objective, Manufacturability, Cost, Yield and Rate, Quality Management and Industrialization. 2. Project Management - Implementation Plan, Business Benefit and Intellectual Property. For the accomplishment of an MRL, all categories need to fulfil the specific level criteria.

2.2.4 Evaluation models

Evaluation is the systematic and transparent assessment in a scientific environment (Widmer & DeRocchi, 2012). It examines effectiveness by the degree of goal achievement and efficiency, looking at the relation of expenses and benefit. In this study, evaluation is defined as the result of an evaluation process as a product, with usable results in form of descriptions, valid interpretations, and recommendations for optimization of the evaluation base and future actions (Balzer, 2005). Two types of evaluation can be described: formative and summative evaluation. Formative evaluation has mainly an optimization function. The improvement of the evaluation target needs a continuous feedback of results to enhance the process further. The formative evaluation deduces specific recommendations for change of action or implementation. The summative evaluation has a control and legitimation function. The final assessment of the evaluation criteria describes a complete lesson learned of the conducted evaluation of the process for the future. For summative evaluation, some results of the formative evaluation can be included, those results can be used for the improvement of the process or for final decisions (Döring & Bortz, 2016). Research in the field of evaluation of programs or projects demonstrates a large amount of shallow information. Details on how exactly evaluations are to be done or specific guidelines regarding this topic are rare. Limiting the research to the industrial or manufacturing sector reduces the results to a minimum. In general, different evaluation approaches are used for programs and projects. In a research study of 2011 conducted by a researcher team from the University of Georgia, several approaches to evaluate projects were examined. The research compared professional standards for project evaluation, and rated them by their utility, feasibility, propriety, and accuracy (Zhang et al., 2011). As a consequence, the Context, Input, Process, and Product (CIPP) evaluation model was found as the most widely applied evaluation model. The model is designed to systematically guide both evaluators and stakeholders in asking the relevant questions and conducting assessments at the beginning of a project (context and input evaluation), while it is in progress (input and process evaluation), and at its end (product evaluation) (Zhang et al., 2011). The CIPP model was already developed in the late 1960s with regard to improve teaching and learning at city schools. The model has been further developed and adapted to various evaluation processes in different sectors of society, health and business and military programs. It has been used for program, project, employee, product, institution and system evaluation (Stufflebeam, 2003). It follows the chronological sequence of the program and analyzes how the individual elements influence the overall result (Stufflebeam, 2003). Its underlying purpose is not to prove, but to improve. The model is configured for use in internal evaluations; self-evaluations conducted by individual service providers and contracted external evaluations. In this study the model is adapted on the CS process of Gassmann to evaluate the focal CS initiative (see Figure 2-1).

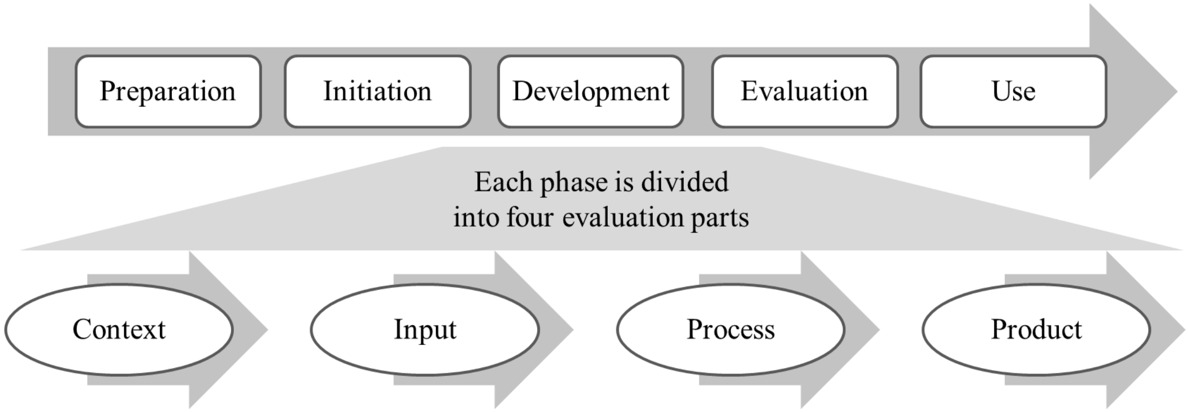

Figure 2-1: Link of CS process and CIPP evaluation model (Own illustration)

It is not easy to measure the success of a CS initiative precisely. Depending on the specification, problem description and previous experiences the results are likely to be different. The value of a CS initiative can be divided into various parts and do not necessarily have to be monetary. Additionally, the evaluation should focus on the complete process, which also includes the openness to the crowd. Therefore, the evaluation method needs to show certain openness and adaptability. Most evaluations are focusing on the cost side and disregard other dimensions. The evaluation model used in this study should be transferable as evaluation basis methodology to various CS initiatives. Determining how CS is used will help to assess the cost, quality and time impact of the new practice (Evans et al., 2016).

2.3 Research Method

The present study is based on a seven-month CS initiative executed in three phases with eight universities worldwide. It is an exploratory, in-depth pilot study design with an analysis of five R&D projects. Topics identified in the case study point to important issues for further investigation. The CS initiative was executed with five units of Siemens AG, a multinational technology company. We executed and studied this initiative from the idea generation over the idea refinement until the idea implementation process. We analyzed it by using the above-mentioned framework. The research design was chosen because of the limited knowledge how CS initiatives in the manufacturing area can be evaluated and how CS can push the development and implementation of manufacturing technologies in a B2B environment. The three CS phases included the idea generation phase on a single-seeker internal platform (Schenk et al., 2017), which is hosted by an external partner. The platform was already used before for external and internal CS initiatives of the firm. In this first phase, students of the eight chosen universities registered on the platform, received information about the challenge and posted business and technical ideas for the digitalization of measurement technologies. The universities were chosen based on the existing network, research focus of the university and research collaboration with the university. The ideas were commented and evaluated by Siemens experts on the platform. The idea providers were surveyed via an online tool regarding the procedure of the first phase (1. student survey). Each idea was evaluated by two experts with eight equally weighted criteria (innovativeness, automation & digitalization, feasibility, performance, implementation, business impact, potential, and flexibility). The second phase of the CS initiative led to an idea refinement of the 33 ideas on the platform. Here, the idea providers produced a short video description of their idea. The platform changed to a closed community of the chosen idea providers and experts. Furthermore, Siemens got into physical contact with the idea providers through trainings on each university campus. The idea providers were again surveyed via an online tool regarding the procedure of the second phase (2. student survey). The evaluation was executed in a pairwise voting by the same experts as in the first phase. Each expert evaluated all ideas. The experts discussed the best ten ideas in a final evaluation meeting. Based on the evaluation score and best fitting, five final idea providers were selected to join the third phase. In the third phase, all idea providers were invited to participate in a one-week prototyping workshop in the manufacturing facility of Siemens. Before this, idea providers and experts further discussed the idea and their possible initiative fields in online meetings or even in local meetings at the university campus. During the prototyping week the idea providers could test their ideas in a real manufacturing environment with input of machinists and employees. The possibility to get further information of already involved and new experts was given. Each day a five-minute pitch per idea in front of the complete group was held, feedback and input could be further discussed and implemented in the next days. On the final day, a presentation in front of eight managers as the evaluation board with an ensuing get-together closed the event. The managers rated the ideas regarding the categories innovativeness, business impact and time-to-market on a scale of one to five. An overall winner was not chosen. As all five teams were already selected for the final phase a further selection was not intended to happen. The idea providers were daily surveyed during the prototyping (3. student survey). In the entire initiative several extrinsic and intrinsic incentives (Schenk & Guittard, 2011) were provided to motivate the idea providers, experts and supporters. These characteristics of CS are not in the focus of this study. The final five idea prototypes were transferred into R&D projects. These R&D projects were analyzed over a period of four months. Here, we used a standardized survey and an MRL assessment tool with the R&D project leaders and conducted interviews with experts and supporters. The assessment was executed three times with two responsible project leaders (R&D and production) per project. Additional data like results of a lessons learned session, meeting records and observations were used in the study. All generated data were included into the CIPP evaluation model. The entire research framework is presented in Figure 2-2 in combination with the CS process of Gassmann. With the mixed-method approach, we assigned qualitative and quantitative methods with a clear structure to each phase and checked the specific context, input, process and product of each phase to evaluate the progress of the initiative and their ideas.

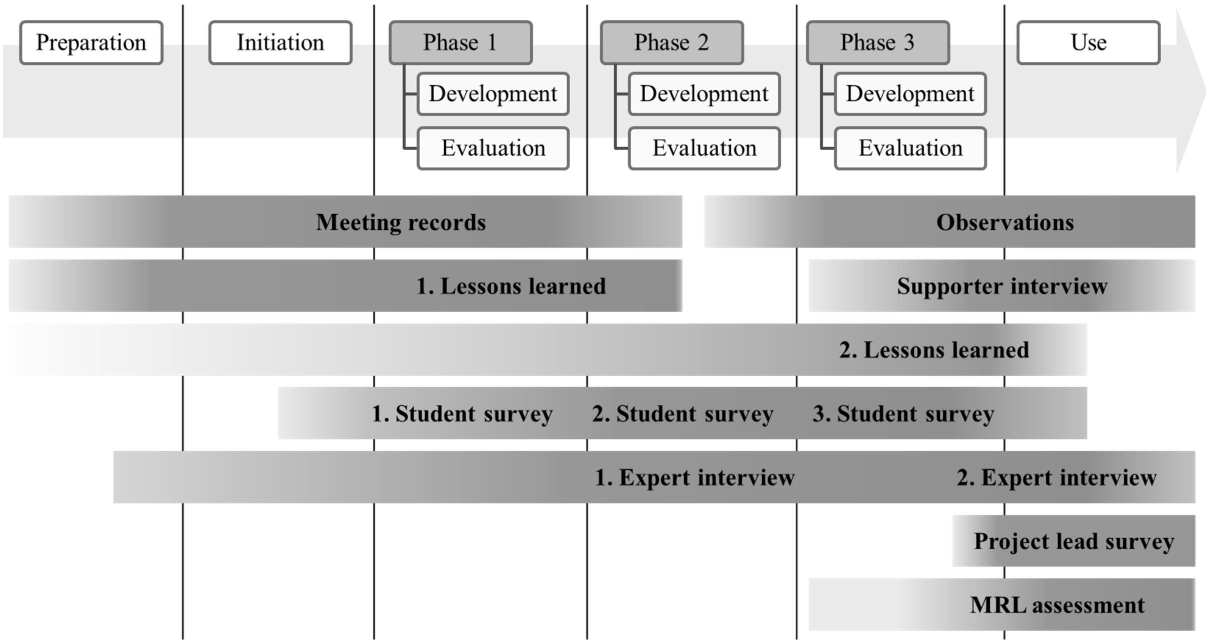

Figure 2-2: Quantitative and qualitative research method over the CS initiative (Own illustration)

2.4 Empirical Findings

In order to obtain an appropriate support for evaluating CS initiatives, it is necessary to define a common understanding of the overall process and the main drivers in each phase. Therefore, we first describe general transferable tasks in the CIPP model evaluation based on qualitative and quantitative data of the initiative. In detail, we describe the findings of the use phase of the analyzed CS initiative regarding the factors: manufacturing technology maturity level and development status, risks and problems, benefits, structure and resources; to outline the acceleration of time-to-market of the manufacturing technologies.

2.4.1 CIPP evaluation model for crowdsourcing initiatives

Gassmann divides the CS process into the preparation, initiation, development, evaluation and use phase. The preparation is the first step and sets the decision for a CS project. In the phase of initiation, the specific question is published to the crowd. The development phase is the submission of ideas. In step four evaluation and selection are done, as well as the appreciation and maybe payment of the participants. The final use phase includes the implementation and deployment of the ideas in the firm (Gassmann, 2013). This process is used in this study as evaluation framework of the CS initiative. Table 2-1 illustrates the main tasks in CS initiatives over the entire process following the CIPP model.

Table 2-1: CIPP evaluation main task in CS initiatives (Own illustration)

	Context	Input	Process	Product
Preparation	Clarification & definition - Stakeholder objectives - Initiative background - Possible problems	- Instrument alternative assessment - Concept decision - Resource planning process	Definition & decision process - Concept development - Stakeholder identification - Problem detection - Process criteria	Clear overview: - Stakeholder objectives - Background - Problems
Initiation	- Further stakeholder objectives - Goal definition - Goal and objective consistency - Result definition for all phases - Possible problems	- Crowdsourcing category & instrument - Platform sufficiency - Resource planning process for all phases	Definition & decision process - Problem description - Time scheduling - Procedure planning - Marketing sufficient - Legal background qualified	Clear overview: - Problem description - Initiative procedure - Time schedule
Development	- Problem description - Publishing process/ platform - Enough support for the participants	Rechecking of planned resources - Timing - Staff - Sufficiency	- Rechecking of plan (initiation) - Sufficiency of development process	- Planned results and goals - Further outcomes

Table 2-1: CIPP evaluation main task in CS initiatives (Own illustration)

	Context	Input	Process	Product
Evaluation	Evaluators - Background (personal & work-related) - Connection with the initiative	Rechecking of planned resources - Timing - Staff - Sufficiency	- Rechecking of plan (initiation) - Transparency of evaluation process	- Planned results and goals - Further outcomes
Use	- Clearly defined projects or open work environment	Rechecking of planned resources - Timing - Staff - Sufficiency	- Rechecking of plan (initiation) and supplemented changes during the ongoing initiative	- Planned results and goals - Further outcomes

In the following we will give a short summary of each CS phase and their CIPP main tasks.

During the preparation phase of a CS applicatons, the problem is identified, and solution strategies are discussed. The overarching question is whether a CS initiative is the correct concept in this case. In terms of the CIPP model, the product of the preparation phase is mainly the outcome of the context evaluation, the defined stakeholder groups and the discovered and collected needs and objectives of the stakeholder groups.

The initiation phase includes the specific formulation of the problem and question. The time schedule and plan of procedure is developed as well as the process criteria defined. The result of the initiation phase is the broadcasted initiative and problem description to the crowd. A defined detailed time and process plan is set up as well as the staff responsibilities and process criteria. Furthermore, goals are fixed and assigned to the different steps of the initiative. The goals are basically the outcomes which get evaluated in the product section of the following three phases (development, evaluation, and use).

In the development phase, ideas and/or solutions are submitted and further refined. As product of this phase, the number of registered/attending participants, amount and quality of submitted ideas are reviewed.

After receiving the input in the development step, the submitted ideas and deliverables are evaluated and the winners selected. The achievement of the initial objectives and goals are evaluated and reviewed. Furthermore, an evaluation is done whether there are further outcomes which were not considered in the initiation phase.

The last step of the CS process is the use of the results in the firm. This includes the implementation and utilization of the ideas and results in manufacturing or further development of the ideas. To evaluate this phase, a termination criterion needs to be defined. The planned goals are evaluated and reviewed e.g., number of new employees, implemented ideas and impulses for new projects.

Taking the most important parts of the CIPP evaluation model of Stufflebeam the following parts are included in a final report of CS initiative: a description, the evaluation purpose and procedure, the evaluation instruments and questions, the data analysis method, the results and the conclusion.

The described evaluation procedure is a recommendation for the practical use in CS initiatives. Each task needs to be checked and adapted for the individual initiative. Detailed questions depend on the basic structure of the initiative and the involved stakeholder groups. The basic structure can be adopted for specific CS concepts, such as intermediaries, open source, company internal initiatives, marketplaces for creative ideas and public initiatives etc.

2.4.2 Use phase model application – Crowdsourcing for manufacturing technologies

In order to define the time-to-market acceleration of manufacturing technologies we focused on the use phase of the CS initiative at Siemens. The five prototypes of the one-week prototyping workshop were handed over by the project leader of the initiative to a responsible person at Siemens to become R&D projects and pursued further. We mainly received our information for the use phase from a project leader survey, an MRL assessment and further observations in the follow-up of the one-week prototyping workshop. Furthermore, supporter and expert interviews as well as the third student survey were included. The project leader survey was executed three times as well as the MRL assessment of each project. Thereby, we generated concrete values for each project, which enable the comparison of the five projects. The project leader survey included the four CIPP steps to evaluate the entire use phase. The survey was selected as an appropriate method for comparing the status of the different projects. Open and closed questions were mixed in the survey to increase the information transfer with comparable results. The questions were partially described as a negation to provoke the participants to keep on thinking about each question separately and not always tick the same side of the boxes. Questions and categories of the survey were developed based on the innovation scorecard. The innovation scorecard is structured in five main categories (innovation strategy, innovation process, innovation culture, resource deployment and organizing for innovation) with several questions each (Grimm & Sommerlatte, 2003). The following five categories were related to the CIPP: 1. Context: Development Status, Problems & Risks; 2. Input: Resources; 3. Process: Structure; 4. Product: Benefits. For the assessment, it is important to review the five R&D projects separately. Two project leaders per project rated six to five questions, depending on the category, in a scale between x=0 to x=4 in the time period T0, T1 and T2 - the higher the value X the better the project. All criteria values per project over each time period were calculated with the mean.

$$X = \frac{\sum x}{N}$$

$$X = mean;\ \Sigma x = sum\ of\ all\ scores; N = number\ of\ cases$$

Advantages of the mean: It is the only measure of central tendency that uses the information from every single score.

Context

We included questions for the development status regarding project results, stakeholder requirements, new field of application as well as customers' and cross-functional understanding of the project.

Table 2-2 illustrates the change of the development status over the time period T of the different projects. The highest reachable value per project was 24. The development status of Project A stayed constant over the time periods T. A growth was not detectable which is referring to the waiting position of the project team members for external offers which dragged on a longer time than expected. Project B was clearly growing from 6 (T0) to 11 (T3) due to new stakeholders. Project C stayed in an already highly advanced status 15. Project D was directly implemented at T0. Project E was cancelled after T0 due to no direct field of application in one of the involved business units. Both projects (D & E) were presented only once at T0 and not included in the second and third survey round.

Table 2-2: Use phase analysis - Context: Development status (Own illustration)

CIPP	Time	Criteria	Project A	Project B	Project C	Project D	Project E
Context	T0	Development status	11	6	15	10	6
	T1	Development status	12,5	9	15	-	-
	T2	Development status	10	11	15	-	-

The questions on problems and risks dealt with missing financial resources, relevant team members, technical and quality issues, missing management support and potential risks. Thereby, an inverted scale was used for the questions.

In Table 2-3 the change of the problems & risks is illustrated over the time period T. The highest reachable value per project was 20. Project A, C and D already had the problems & risks defined widely during the first survey round. Project B could frame this part widely during the three-time periods. This progress is directly linked with the development status of project B. Project E had the lowest initial position.

Table 2-3: Use phase analysis - Context: Problems & risks (Own illustration)

CIPP	Time	Criteria	Project A	Project B	Project C	Project D	Project E
Con-text	T0	Problems & risks	16,5	10	18	17	6
	T1	Problems & risks	18	12	15	-	-
	T2	Problems & risks	18	19	18	-	-

This data is representing the context of the use phase. The context indicates under which setting (affected problematic areas) and requirement the projects are further developed inside the firm. We assigned the criteria development status and problems & risks to the context because each CS initiative must check in their use phase, how the settings and requirements are defined in their application area.

Input

The resources, funding, and timing which should be defined in the initiation phase were only partially planned for the use phase. Problematic is the lacking knowledge about which projects will come out of the previous phases and where they will be positioned in the firm in the future. Even though this is hardly changeable for CS initiatives with multiple finalists, the process of specifying the resources needed has to be planned in a certain way. In the survey, we analyzed the resources in terms of available equipment, officially planned, funded and allocated resources, idea provider involvement and new team members involvement.

The input for each project over the time period T is shown in Table 2-4. The highest reachable value per project was 24. The data indicates that project A, B, C and D started initially with high number of resources. While project A values decreased over the periods due to the waiting for external offers, project B resources increased largely in the third period T2. Project C has consistent high resource numbers. Project E started with the lowest resources which also resulted in no further development of the complete project.

Table 2-4: Use phase analysis - Input: Resources (Own illustration)

CIPP	Time	Criteria	Project A	Project B	Project C	Project D	Project E
Input	T0	Resources	13	11	20	11	3
	T1	Resources	9,5	9	18	-	-
	T2	Resources	8	18	19	-	-

This data is representing the input of the use phase. The input outlines how the project was supported with necessary resources. We assigned the criteria resource to the input because each CS initiative must check in their use phase, how the resources are planned and allocated for the development of the project in their application area.

Process

The process of development was also not defined in the initiation phase based on lacking process knowledge. In the survey we included question for the structure regarding the priority and work focus, project structure, efficiency of the setup, communication with interfaces and systematic search for know-how sources and development partner. Important in this category is the actual development process of the projects and how it is performed.

The results of the project lead survey of the process are shown in Table 2-5 over the time period T. The highest reachable value per project was 20.

Project A and C were similar rated at T0 and stayed constant over the time periods. Project B started even slightly lower than project E but developed a huge step in the third period T2. Project D started with a low value and still reached the planned results for the project.

The context, input and process data of the projects showed that project A and C had at the beginning of evaluation a very good project environment regarding development status, resources and structure. The values of project B significantly improved over the time periods. Project D was already implemented, and the further development of project E was stopped at T0.

Table 2-5: Use phase analysis - Process: Structure (Own illustration)

CIPP	Time	Criteria	Project A	Project B	Project C	Project D	Project E
Process	T0	Structure	13,5	4	14	8	5
	T1	Structure	12	4	13	-	-
	T2	Structure	12	13	14	-	-

This data is representing the process of the use phase. The process characterizes how the project was setup in the firm and how efficient their workflows are. We assigned the criteria structure to the process because each CS initiative must check in their use phase, how to structure the development of the project in their application area.

Product

The product step of the use phase was analyzed based on the benefits in terms of cost savings, positive benefits for the working conditions in the production environment, productivity, lead time reduction and, impact on the quality of the final product. Table 2-6 demonstrates the benefits values over the time period T. The highest reachable value per project was 20.

Projects A, B & C unchanged over time. Project A and C were rated high due to direct impacts on the applied manufacturing facility. Project D was already implemented, and the further development of project E was stopped at T0.

Table 2-6: Use phase - product analysis of the initiative - product (Own illustration)

CIPP	Time	Criteria	Project A	Project B	Project C	Project D	Project E
Prod-uct	T0	Benefits	16	9	16	13	8
	T1	Benefits	17	9	16	-	-
	T2	Benefits	17	9	16	-	-

This data is representing the product of the use phase. The product indicates how the designated benefit definition situation of each project is. We assigned the criteria benefits to the product because each CS initiative must check in their use phase, how the firm benefits from the results in their application area.

This small amount of data already demonstrated the individuality of each project. The data was linked with the final MRL assessment. The MRL assessment relates to information of the project leader survey as well as observations, expert, and supporter information. The objective fundament with several categories and criteria supports a clear evaluation process of the outcome. The average result of the five projects for the assessment periods is shown in Table 2-7. The average value is a comparable figure between the different projects. The target of MRL 2 after the third phase and MRL 3 within time period T2 have been achieved for three projects. Two of the projects did not show a high MRL and furthermore, did not show a large development over the time periods assessed. Project E is not further developed by any involved initiative participant and therefore failed in view of the set target. The project B is also below the target line, while it shows only a small raise in the last period T2, but no big difference is measurable in the MRL assessment.

Table 2-7: Use phase - product analysis of the initiative - MRL assessment (Own illustration)

		Project A	Project B	Project C	Project D	Project E
T0	MRL value	2,9	1,9	3,7	5,8	2,6
T1	MRL value	3,5	1,9	3,8	-	-
T2	MRL value	3,6	2,1	4,2	-	-

The project leader survey was also utilized to create a possibility of explaining the situation shown in the MRL assessment. Questions such as 'why one project is less successful than the other' is interesting for the evaluator and can be read out of the survey results. When reviewing the project leader survey, project B showed the largest differences between the different time periods. New financial resources were allocated to the project as well as new development partners involved. The most successful projects A and C had the highest benefits, best structure, defined problems & risks and a constant development status. The management support was given as well as the idea providers included, and technical issues defined. Project A did not reach the same MRL like project C based on external resource influences. Project D was direct implemented as prototype with a high benefit and clear problems & risks. The benefits did not develop further for all projects, as they were identified during the one-week prototyping workshop of the initiative and no new benefits were detected, while all other categories made large progress.

Summarizing the outcome of the product, four projects of the five finalist projects are ongoing within Siemens. Three of them were assessed above MRL 3 and one project was on the rise. At the end of our analysis, project A and C were R&D projects within one business unit within Siemens and the idea providers of the initiative were actively involved. Project B was a research project at the involved University in China with Siemens integration – idea providers of the initiative were involved. Project D was already implemented during the workshop. Project E was not further pursued by Siemens participants of the initiative but was based in another project within Siemens. The applicability within one business unit was examined during the workshop. The assessment of the projects and the evaluation of the CIPP show a first glance that CS has an influence on the development and implementation of manufacturing technologies in a corporate environment. The defined goals were reached for three technologies. The initiative was a successful event considering the objectives and planning in advance with several aspects for improvement which are results out of this evaluation.

The data implicates that the CS initiatives provided Siemens with external technical knowledge and resources. The simultaneous engagement of internal R&D activities with the CS initiatives enabled the development of manufacturing technologies over a short time period with a high

MRL. The technologies were evaluated, adopted and partly implemented in the firm. The CS initiative pushed the manufacturing improvement and thereby accelerates the time-to-market of new products.

2.5 Discussion and conclusion

2.5.1 Theoretical implications

The present study makes several theoretical contributions. First, the analyzed CS initiative addresses a so far non-listed CS application area (Whitla, 2009; Kleemann et al., 2008): manufacturing technologies with their development and implementation. Such study is the first on a CS initiative starting from the ideation phase via prototypes in a real-manufacturing environment and final transfer into R&D projects. The use of CS initiatives allows the firm to elaborate new practices to leverage innovation and ensure competitive advantages. It illustrates that the involvement of an external crowd creates new ideas, resources, internal management support and that CS is applicable in a manufacturing perspective to develop ideas to real processes, services or products in the manufacturing area and implement them.

The second contribution of the present study is a practical guideline to evaluate the entire process of CS applications. Therefore, we combined the CS process of Gassmann and the CIPP evaluation model. The model helps to evaluate and improve the CS application and supports the evaluator and stakeholder of the application. Information about the efficiency of CS efforts are generated and enable improvements from one CS initiative to the next CS initiative. The descriptions and instructions are specifically defined for CS. Such guideline can be used as a basic framework but need to be defined for each specific case. It addresses the need of evaluation guidelines to standardize CS and make it comparable and evaluable in the B2B or manufacturing sector. The paper helps to assess the cost, quality and time impact of CS by determining and evaluating CS applications.

Finally, a key contribution of the present paper is to actually apply CS in manufacturing to accelerate time-to-market of manufacturing technologies. Time-to-market of products is linked with the evaluation, adoption and routine of technologies (Zhu et al., 2006). The assessment of the impact related to the problem-solving performance, namely the development time (Afuah & Tucci, 2012; Atuahene-Gima, 2003) of CS is covered in our evaluation. The study implicates that CS has an impact on these factors for manufacturing technologies. The maturity assessment of the technologies in the use phase showed that a certain MRL was reached with the initiative and three of five technologies were further developed in R&D projects. Main drivers for these results are established in the analyzed criteria: development status, problems & risks, resources, structure, and benefits of the project.

2.5.2 Managerial implications

The developed evaluation model is a first approach to measure CS initiatives from a manufacturing technology perspective. The evaluation tool built upon literature and one exploratory, in-depth pilot case study with multiple projects. It is a combination of the comprehensive CS process of Gassmann and the CIPP model. In a first step, managers can decide, if a CS initiative is useful for their purpose. If the CS initiative is chosen, the model helps to define, how the initiative can be executed. It is important to define the surrounding conditions of the evaluation in advance to limit the evaluation process. By using the model, CS applications become evaluable and comparable. The effort and efficiency of the CS application is defined for the firm. For manufacturer CS will be a new practice to leverage cost reduction and process efficiency. It supports the manager to accelerate the time-to-market of new products by accelerating the development and implementation of manufacturing technologies. New innovative technologies are assessed with respect to their value to the company and a prototype manufacturing readiness level of about 3 is reached, if the CS application is well designed and incorporates the real-manufacturing environment and knowledge of the firm. For industrial firms, it is important to leverage the CS potential as external technical knowledge (Chesbrough, 2003), increased resource efficiency (Eisenhardt & Tabrizi, 1995), and innovation speed (Akman & Yilmaz, 2008). It enables to react fast on and assess new emerging technologies (Teece et al., 1997). The study illustrated that some technologies are more mature than other technologies. The results of the one-week prototyping workshop determined the basis for each R&D project. To leverage CS potential, firms have to monitor all analyzed criteria. Especially, transparent benefits (cost savings), a well-structure (involvement of idea providers), defined problems & risks (no financial resources) and a constant development status (clear application and stakeholder requirements) are key elements to accelerate the time-to-market with manufacturing technologies.

2.5.3 Limitations and future research

Although the results of the study provide several contributions to the CS applications in the manufacturing perspective, their acceleration of time-to-market and an evaluation guideline for CS initiatives, the present study has certain limitations that should be considered when interpreting the results. These limitations provide a starting point for future research. First, the insights are limited to a single in-depth exploratory study design because only one case was chosen, in which the firm is actively using CS to develop new manufacturing technologies.

Thus, the gained insights to develop and use the evaluation model and analyze their usability are limited to such case. Adopting to a multiple case study design would provide the potential for cross-case analysis, which is not possible at present. Thus, we do not strive for generalizability in our results. Future research could also conduct further empirical studies to validate or extend the findings of the present study through quantitative studies. Second, the present study analyzed the time-to-market acceleration for manufacturing technologies without defined time values as baseline. There is no comparison with similar approaches like R&D cooperation, internal R&D etc. More specific, the findings are not quantifiable compared with procedures with the same focus and amount of resources, timeframe, setup, and support. The identical limitations concern the presented evaluation model. The model needs to be transferred on other CS initiatives to standardize the methodology and validate it. In this study, all findings are based on this exploratory pilot study. For a model validation various CS initiative must apply the model and address the defined tasks over the entire CS process. Third, the present study was based on a German manufacturer, and the results could differ in another cultural or industrial setting. Future research should investigate whether these findings hold under other conditions. Fourth, we used criteria and an MRL assessment that implicate the acceleration of time-to-market of manufacturing technologies. Our list may be incomplete. A common understanding of the criteria is not established inside the evaluation network (development status, resources, benefits etc.). Finally, we recommend connecting the CS application results with the dynamic capabilities theory of Teece to derive important capabilities to leverage the potential of CS in firms.

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3 Development of a Technology Evaluation Score Model for Manufacturing Technologies

3.1 Introduction

Knowing the actual and applied value of manufacturing technologies is fundamental for the firm's competitiveness thus enabling the selection of the superior technologies considering the limited R&D resources and setup of that firm. From the manufacturing perspective, the firm needs to establish production processes, prepare facilities for production ramp up, and improve manufacturing yields for profitability. Evans et al. (2016) stated that earlier practices such as focusing on product costs, quality and time are no longer enough to ensure competitive advantages in the manufacturing industry. New technologies arise every day and firms need to be able to react fast and assess them (Teece et al., 1997). They must be evaluated, adopted and routinized in the firm (Zhu et al., 2006). While a variety of evaluation models for manufacturing technologies exist in literature (Dengler et al., 2017), most of them focus only on business aspects or selected points of the technology or they are too complex to be actually applied in the industry. Recently, researchers started to also include agile processes in these evaluation systems such as proactive management (Schönmann et al., 2016) or cycle-oriented evaluation (Dengler et al., 2017) to constantly assess the technology and thereby increase the competitive advantage of the firm. Thereby, many models concentrate on the strategic technology management (TM) level with different production outputs for demands and order winning criteria (Miltenburg, 2005). Environmental issues play a major part in strategic manufacturing decisions (Azzone & Noci, 1998; Pun et al., 2002). At the operational TM level, the exploitation of a technology, environmental criteria are not considered in a holistic evaluation model. Furthermore, social effects, e.g. employment rate changes or other societal impacts, are lacking due to their usually reflection in the macroscopic contexts but not on the microeconomic level of a firm (Brandenburg et al., 2014). In this paper the technology evaluation score (TES) model, which has been developed by the authors, is investigated with respect to the important criteria at the operational TM level. Beside that the model addresses the increasing complexity of manufacturing (ElMaraghy et al., 2012) and challenges in the implementation process (García A & Alvarado I, 2013) in a more industry-related model. García A & Alvarado I (2013) listed the investment justification process, decision and analysis process, lack of knowledge among others as main problems in the implementation of advanced technologies. We assume that the combination of strategic evaluation models as Dengler and Miltenburg with the integration of social and environmental criteria helps firms to increase competitive advantage by addressing these problems in a standardized way at the operational TM level. In the next section we provide the theoretical background to understand the field of application and evaluation focus. Afterwards we describe the research methodology and explain the empirical findings with a sensitivity analysis as well as a use case of the developed model. The discussion and conclusion lead to the assumption, that the evaluation of technologies at the operational TM level enables competitive advantage for the firm by standardized evaluation and prioritization of complex manufacturing technologies during their development and implementation.

3.2 Theoretical background

3.2.1 Operational technology management level of manufacturing technologies

Firms are facing a multitude of challenges, like justification of investment decisions, conflicting objectives, or lack of knowledge of the benefits (García A & Alvarado I, 2013), when choosing and implementing advanced manufacturing technologies, defined as any equipment or methodology that is part of the production system for improving performance (Chuu, 2009). Consequently, not only at the strategic level the assessment and selection of manufacturing technologies is crucial in order to assure the competitiveness of a firm (Phaal et al., 2004). The TM consists of three level - corporate, business, and operational (Skilbeck & Cruickshank, 1997). “Corporate” is concerned with the multi business activities in respect to the world market (Perrino & Tipping, 1989). “Business” links the technological activities and market focus to ensure competitive advantages in the firm. In this area several tools were developed to manage technologies (e.g. (Betz, 1993; Steele, 1989). “Operational” addresses the internal R&D and innovation management of the business (Twiss, 1992). Cetindamar et al. (2009) defined six generic TM activities: 1. Identification, 2. Selection, 3. Acquisition, 4. Exploitation, 5. Protection, and 6. Learning. This study focuses on the exploitation activity at the operational TM level. The technology was internally identified, selected, and an acquisition strategy defined (Probert et al., 2000). In the exploitation activity the desired profit or other benefits can be generated in the firm. The implementation, absorption and operation of the technology are required to lift these benefits. The production processes and manufacturing systems technologies are linked to the product context (Phaal et al., 2006). They are key drivers for cost reduction (Schuh et al., 2014) and process efficiency (Klocke et al., 2014) as well as product functionality improvement by enabling new product features e.g. by 3D printing of components.

3.2.2 Technology evaluation models

A variety of approaches and models for evaluating manufacturing technologies have so far been presented in literature (Dengler et al., 2017) on the strategic TM level to obtain competitive advantages in the firm. Dengler et al. (2017) highlighted that cost, quality, volume, flexibility, sustainability and product feasibility are the evaluation criteria with the highest usage frequency (Dengler et al., 2017). The systematic method of Miltenburg (2005) uses similar criteria for the evaluation of factories and international manufacturing to define a manufacturing strategy to be first in the market. His evaluation is based on the quality, delivery, cost, flexibility, innovativeness and performance criteria in regard to the product and volume. Most of the models focus on the business needs and the evaluation of the monetary value of technologies (Chan et al., 2000). The cycle-oriented evaluation model of Dengler integrates new criteria as interconnectivity due to the gain in importance of data transmission and exchange in production (Dengler et al., 2017). While this leads into the right direction, increasing complexity of manufacturing (ElMaraghy et al., 2012) also require technology evaluation models at the operational level. The integration of environmental and social aspects with economic considerations, known as the triple-bottom-line dimensions of organizational sustainability (Elkington, op. 1998, 2004), has continuously gained relevance for managerial decision-making in general and operations management (Kleindorfer et al., 2005). The employee involvement is an essential component in the decision-making and financial success of the firm (Rao et al., 2010). Holistic models are established in the sustainable supply chain management (Brandenburg et al., 2014). In this study we adopt these factors onto the operational TM of manufacturing technologies to address the problems in the implementation process of manufacturing technologies.

3.3 Research method

The research is a deductive approach to prove the assumption to increase the competitive advantage of firms by evaluating technologies at the operational TM level. The model was developed and applied in a manufacturing plant of the Siemens AG. Beside the listed criteria of Dengler and Miltenburg, the model incorporates the innovation scorecard (Arthur D. Little, 2001), monetary value approaches like cost utility analysis, net present value, return on investment, and payback period (Chan et al., 2000) and further important criteria of the triple-bottom- line. All approaches were combined to evaluate the overall technology impact on the manufacturing. A sensitivity analysis was executed in the model-building phase to identify irrelevant model inputs (Felli & Hazen, 2004) and to demonstrate to potential users the validity of the results of the model (Gass, 1983) before the utilization. Sensitivity analysis is nothing but the process of checking the robustness of the obtained output. To establish the sensitivity, the model was 2000 times used with randomly generated weightings and ratings for one technology. Afterwards, the model has been applied together with project managers on eighteen different manufacturing technology projects. Furthermore, the model has been discussed and reviewed with various shop floors responsible. The management contributed and agreed on the weightings of the criteria. Herewith, research data was collected, and the model was validated with direct feedback for improvements.

3.4 Empirical findings

The outcome of the model is a TES. It includes weighted main criteria of economic efficiency, quality, product functional capability, environmental health and safety, strategy, resource input, and social aspects. The partial scores of the main criteria result from the monetary approaches for the economic efficiency and multiple questions for non-monetary criteria, which are answered by technology experts and project stakeholders and summarized afterwards.

3.4.1 Technology evaluation score model description

The model is used for efficient technology decisions at the operational level. The decision is generated by determine a TES based on 7 factors. This evaluation is executed for all considered technologies. The technology development and implementation are executed for those technologies, which achieve a certain limit (e.g., at least a minimum score of 50 %). Other criteria like assigning a certain amount of R&D budget are also possible. Figure 3-1 illustrates the TES model.

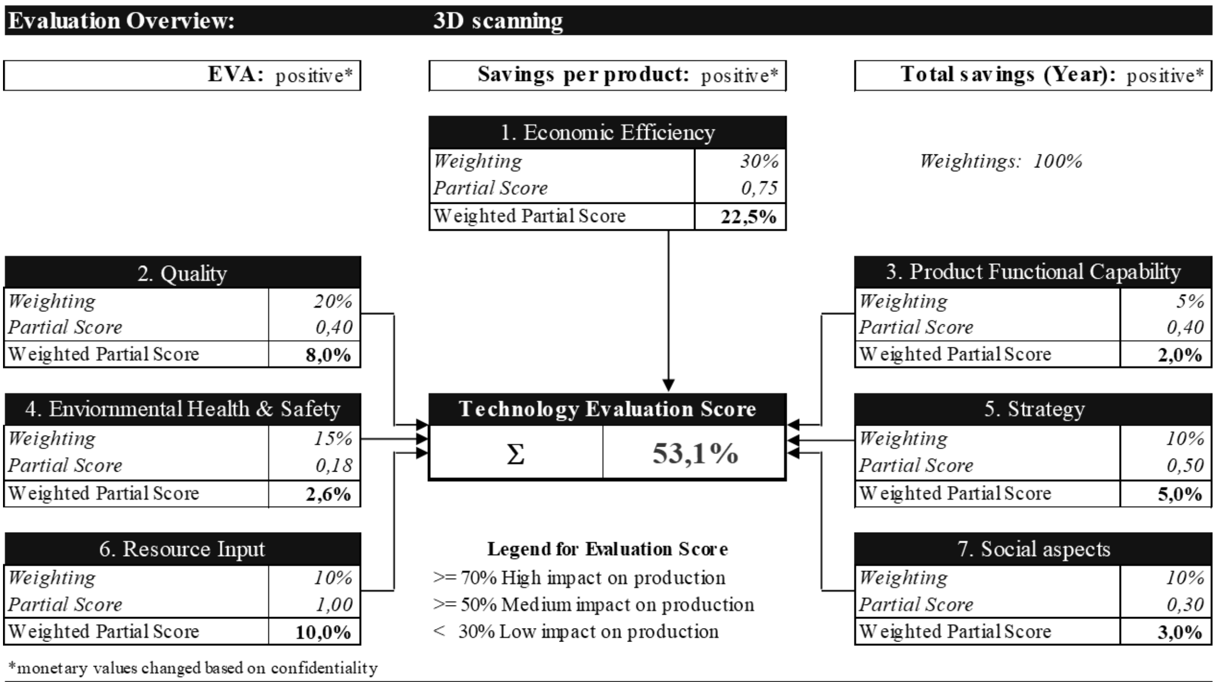

Figure 3-1: TES Model - Overview (Own illustration)

The TES is calculated with the following formula:

$$\text{TES} = \sum_{i=1;\, k=1}^{N} \Sigma(WSC_i\ x\ RSC_i)\ x\ WC_k$$

TES: Technology evaluation score; WC: Weighting of main criteria; PSC = $\Sigma(WSC_i \text{ x } RSC_i)$: Partial score of main criteria; WSC: Weighting sub criteria; RSC: Rating sub criteria

The economic efficiency score is based on the cost saving per product, amortization, return of investment and economic added value. To define the cost savings, a comparison of the old and new manufacturing process is executed. All manufacturing costs per part are considered in the comparison (e.g. material, machine and labor cost etc.) (Reinhart et al., 2011; Schuh et al., 2012). Additionally, quality non-conformance costs are included as well as one-off effect cost savings (e.g. scrap value). The amortization, return of investment and economic added value are calculated with the capital expenditures, abbreviations, R&D costs linked to the cost savings and the production load (Koho, 2010). The outcome of the calculation is considered as part of the utility analysis, which is used for the other criteria. In the utility analysis, the operational stakeholder rate four questions in concern of their fulfilment level in a given scale. Each of the four questions is weighted by the management before to adapt the model onto the firm requirements. The fulfilment level is multiplied with the question weighting. All partial scores are summarized to define the partial score of the main criteria (e.g. quality - 0.4). The quality comprises the improvement of the production quality (accuracy, durability, first-pass-yield etc.) (Koho, 2010), reduction of the reject rate, acceleration of quality notification solving, and definition of corrective and preventive actions of the production. The product functional capability includes questions concerning individual product functional improvements, reduction of the life cycle cost, and improvement of the reliability, availability, maintainability, durability and safety of the product (Reinhart et al., 2011). The environmental, health and safety (EHS) criteria describe environmental factors (less production resources and tools, less waste etc.) (Stauder et al., 2016), improvement of work safety (physical integrity, injuries, and health burdens), work simplification, and workload balance. The strategy contains relevant questions about the intellectual property, patent, support of existing and general firm strategy, and the strategic network (suppliers, customers, partners etc.). The resource inputs comprise the effort for implementation, available knowledge and capacities (machine, labor, hardware, software etc.), and possibility to transfer the technology. The social aspects contemplate the employee training of new work skills, worker empowerment, career development of the technology operator, and overall social influence of the technology.

3.4.2 Sensitivity analysis of the technology evaluation score model

The target of the sensitivity analysis is to assess the impact of the weighting factors as well as the partial scores, as the weighting factors are chosen by expert judgement in general to rate different technologies and for the partial scores by experts for individual technologies. The sensitivity analysis was executed with the "3D scanning" technology to validate the influence of the partial scores in combination with the weighting of the criteria on the TES. To establish the sensitivity, the model was used 2000 times via randomly created weightings and ratings for the technology. Figure 3-2 shows the distribution of the impact factors in the 2000 evaluation.

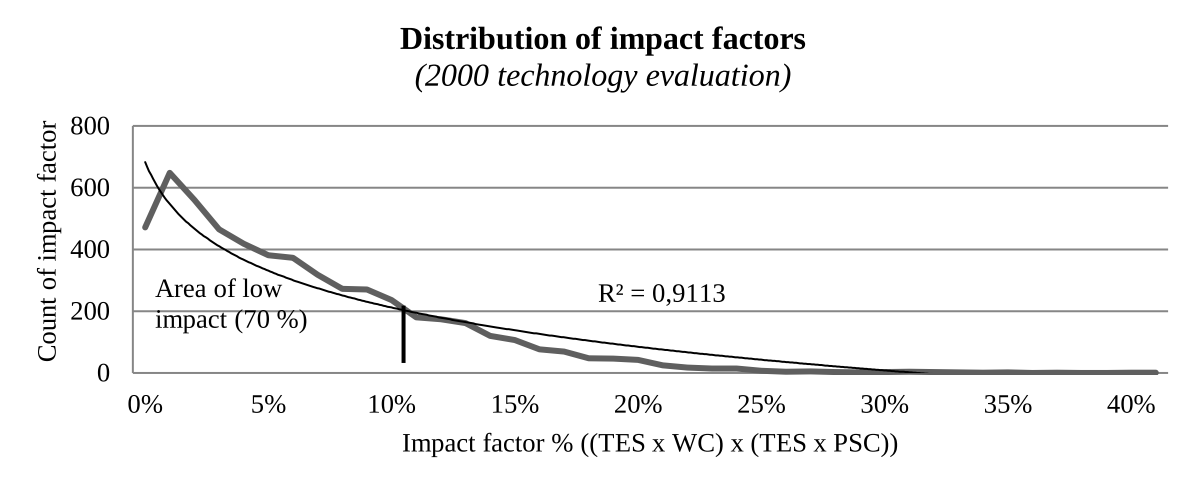

Figure 3-2: Distribution of impact factors on TES – Weighting and partial scores (Own illustration)

According to the sensitivity analysis, changing the weight and the partial score of the criteria alters the decision for or against a technology. Considering another weighting of a criterion or rate a criterion differently results in a shift of the TES. We calculated the impact factor by multiplying the influence of each weighted main criteria on the TES with the influence of the partial score of each main criterion on the TES. Taking the 2000 randomly created evaluation into account, most weightings in combination with the ratings have no influence on the TES. More than 70 % of the combinations are below the impact factor of 10%. The logarithmic coefficient of determination (R^2) of 0.9113 indicates that the rate of the impact is constantly dropping and then stays constant. Anyhow, the decision-making process is sensitive to the type of criteria, the number of participants involved, and their expertise with the subject, their selection should be carefully done. The data reveals that the model is consistent.

To further validate the model and analyse the data, we executed the second part of the sensitivity analysis by taking a detailed view on the TES of the evaluations. The figure 3-3 demonstrates the range of TES within randomly generated 2000 evaluation thus the 3D scanning technology could achieve TES values between 20 and 80 % but considering only the 80% close to the average value the range is between 40 and 60 % taking into account that the TES is featuring a normal distribution.

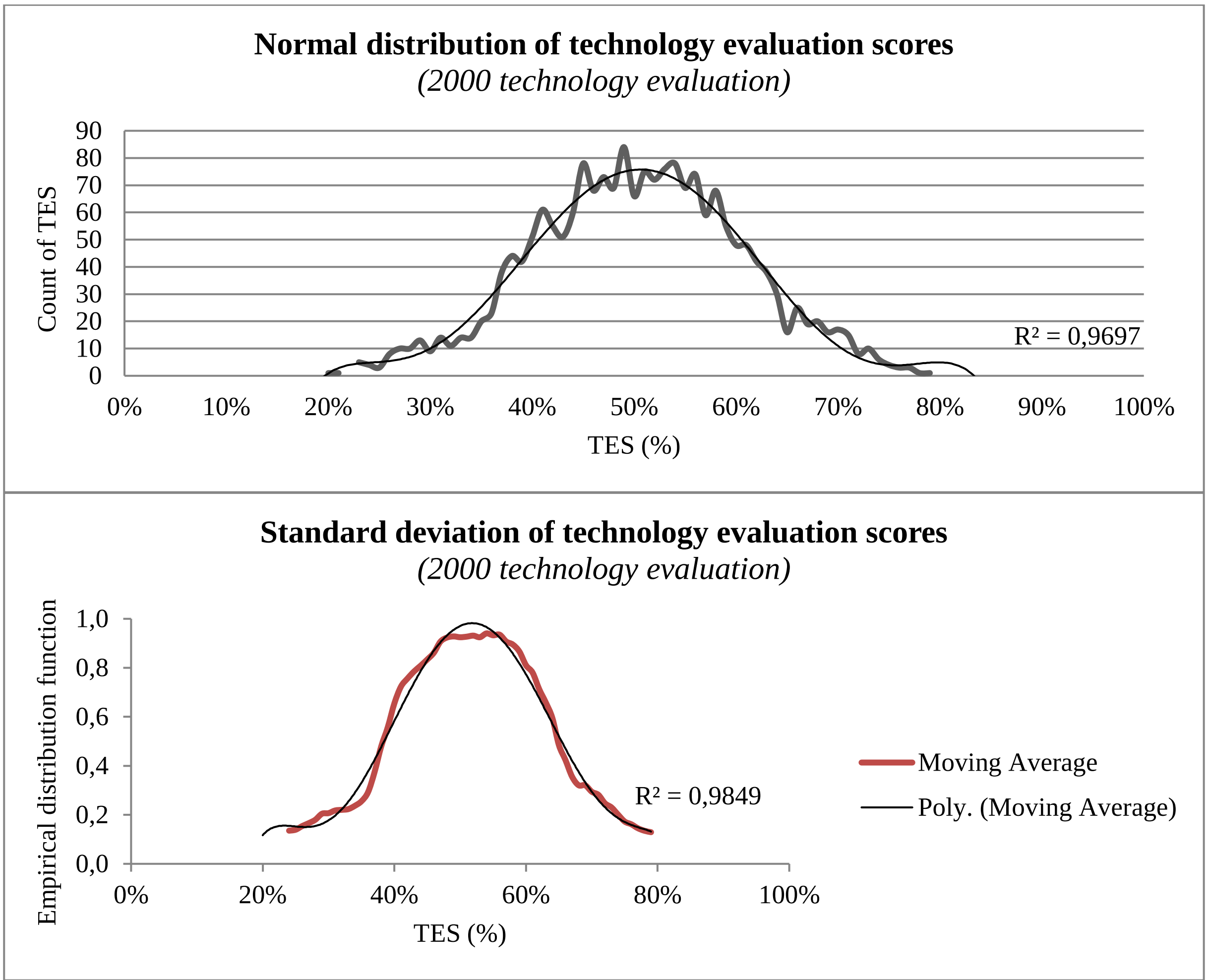

Figure 3-3: Normal distribution (upper) and standard deviation (lower) (Own illustration)

The added polynomial trend line is used for fluctuating data. The sixth-grade polynomial coefficient of determination of 0.9697 and 0.9849 shows a high consistency of the line with the data in both diagrams. Firstly, we counted the distribution of TES over the 2000 evaluation. This data already revealed that the model generates consistent distributed scores. Each of the evaluated technologies has been pre-selected in the firm, so that none of these technologies should reach a score of zero percentage. Due to the complexity in technologies none of the considered technologies can reach a score of hundred percentages of all evaluated criteria.

For example, one technology supports environmental criteria, but such technology is not that cost efficient. A second technology might support the digitalization in the firm but has a bad influence on the social aspects. This complexity is integrated in the developed model.

The standard deviation σ of the moving average of the fluctuating data is 75.4 %. The area of σ is between a TES of 37 % and 64 %. This reveals that the model generates consistent scores, which differentiate enough to prioritize and thus budget that technology development in the firm. Thereby, the weightings and ratings of the different criteria has mostly no high impact on the TES. The model is validated via a sensitivity analysis and can be further validated in their applications. Technologies with a score over 70 % are outside the standard deviation and should be prioritize based on their high impact on the production of the firm.

3.4.3 Multiple-project application of the model

A TES comparison of all technologies in the exploitation activity at the operational TM is shown for one plant of the Siemens AG in Figure 3-4. The comparison illustrates the final TES at a given time. Each evaluated technology has a specific TES.

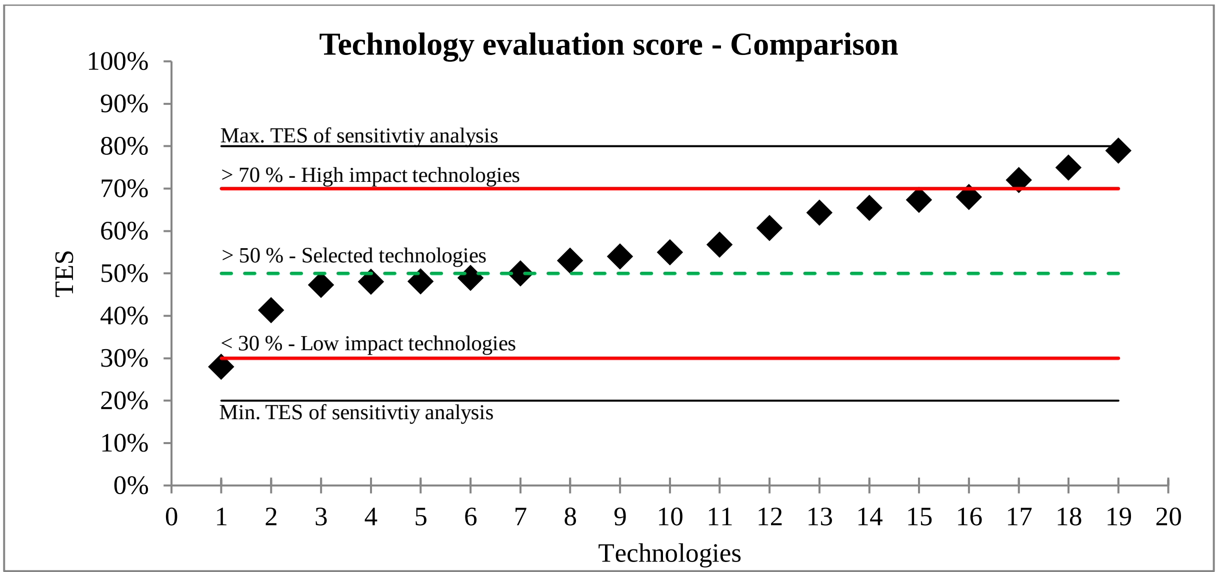

Figure 3-4: TES - Comparison (Own illustration)

In the first application of the model technologies with an evaluation score over 70 % are defined as technologies with a high impact on production. This score is selected based on the standard deviation of the sensitivity analysis and by the management. The data shows that three of the evaluated technologies reach this score. In this case all technologies with a TES over 50 % were selected for further development and implementation in the plant. Only one evaluated technology ranges under the 30 % and is a technology with a low impact on production. The consideration of the model in their daily business and frequent technology planning enables the firm to quickly get an overview of the technologies in development and implementation.

If the management wants to implement technologies with a strategic focus to improve e.g. EHS in the plant, the partial score of EHS could be plotted and technologies with high ratings in EHS could be prioritized. Figure 3-5 reveals a comparison of the TES and one partial score of a main criterion of the technologies.

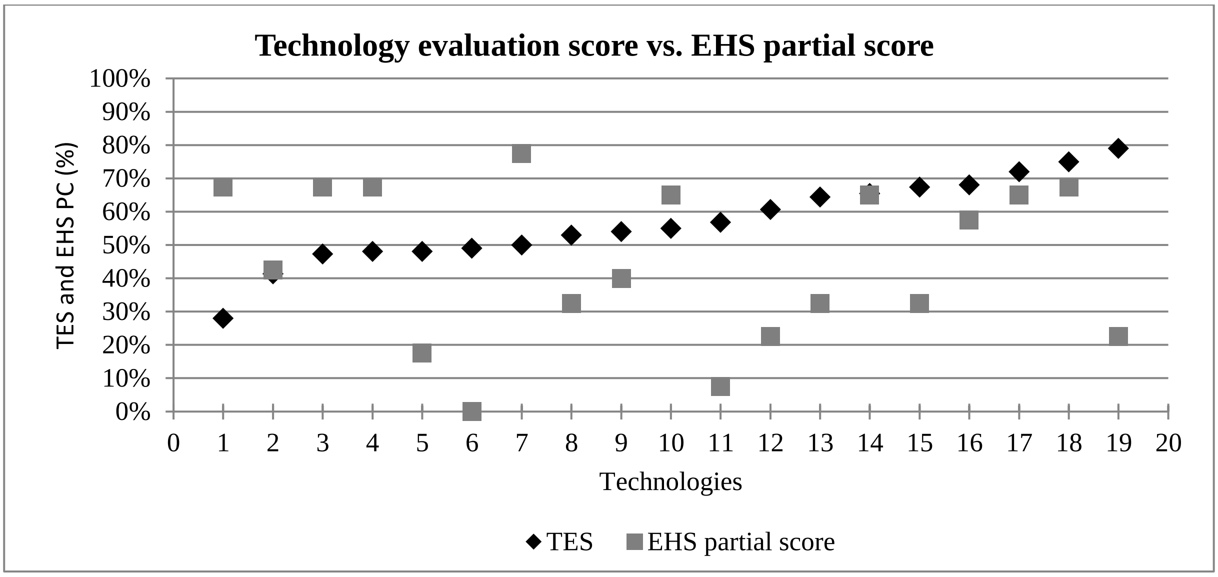

Figure 3-5: TES vs. EHS partial score (Own illustration)

The values demonstrate that some technologies are scored as medium impact technologies with a high impact on the EHS. The utilization of the model enables the firm to overview various technology criteria. The firm can constantly align their technology exploitation based on their internal needs. The model allows an internal customization of the criteria. It helps to constantly manage the technology projects and adapt it regarding the firms need as well as to react on market changes and governmental regulation, and thereby generate a competitive advantage for the firm. To leverage these advantages, the R&D expenses have to be connected with the evaluation outputs in the firm.

3.5 Discussion and conclusion

3.5.1 Theoretical implications

The present study makes two important theoretical contributions. The model was developed by using criteria of the product cycle-oriented evaluation of manufacturing technologies and the manufacturing outputs criteria depending of the product and volume linked with existing operative models in the firm. It addresses the need of industry-related models at the operational level of TM (Skilbeck & Cruickshank, 1997) to increase competitive advantages. The model allows evaluating strategically selected technologies in their application of an individual production environment. It provides insight for the development and implementation of the technology in a manufacturing perspective and supports the decision-maker in the firm. The sensitivity analysis supports the applicability of the model in the industry. The model is valid and generates consistent data for decision maker. Thereby, the impact of the weighting and rating is only crucial in a limited amount of evaluation. The decision-making process with the model is sensitive to the expertise with the subject of the participants as well as the expertise with the model.

The second contribution of the present study is the consideration of social and environmental criteria to access the technology on the microeconomic level. Thereby, a more comprehensive approach of influence factors is used in the evaluation score of the technologies. This creates a bigger picture as well as new shifts in the importance of manufacturing technologies. So far non-considered technologies have the possibility to arise in the application field of the firm. This clearly depends on the market situation and the manufacturing environment.

The problems in the investment justification process, decision and analysis process, and knowledge management (García A & Alvarado I, 2013) during the implementation of manufacturing technologies is clearly supported by the standardized and aligned model within the production and management. Complex manufacturing technologies are connected with influencing criteria to enable the competitive advantage of the firm.

3.5.2 Managerial implications

The evaluation score model was developed with employees, management, customers and users. Through iterative testing, it could be immediately applied in the industrial setting. The comparison of the individual projects with the TES enabled the firm to internally prioritize and budget the manufacturing technologies. The standardized procedure ensured a common understanding of each impacting factor in the plant and drastically improved the cooperation between management, project managers and the shop floor. On the monetary side, business figures can be shown including the direct impact on the product cost. Non-direct monetary factors (e.g. workplace safety) have also been included and hence enhance the importance of some technologies that might not be considered relevant when only looking at the business side. The model supports the decision-making process based on quantitative figures in the firm.

3.5.3 Limitations and future research

The evaluation model has been developed based on a one case scenario. Adopting the model to a multiple case study design in other manufacturing context would provide the potential for cross-case analysis, which is not possible at present. The sensitivity of the criteria was not discussed across different technologies. Further investigations must identify the validation of the criteria across different technology projects. A literature review of social and environmental factors in the manufacturing perspective would help to identify main clusters to create a more generic and transferable evaluation model.

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4 University-industry collaboration indicators for manufacturing technology R&D projects – The industrial perspective

4.1 Introduction

From the industry perspective, the internationalization of industrial R&D aims to exploit location of specific innovation advantages in an globalized environment (Zedtwitz & Gassmann, 2002, S.569). Frequently and rapidly changing technologies in the globalized environments push firms to innovate in order to sustain their performance (Akman & Yilmaz, 2008). From the academic perspective, many universities' rankings take into account the active knowledge exchange in the whole economic and innovation systems (Tijssen et al., 2009; Cunningham & Link, 2015; Laredo, 2007; Shore & McLauchlan, 2012), as well as the entrepreneurial performance (Audretsch et al., 2012; Etzkowitz, 2003; Paleari et al., 2015; Shane, 2005). Both perspectives, are influencing the innovativeness as per the Triple-Helix approach (Etzkowitz & Leydesdorff, 2000) and can be addressed by open innovation (OI). OI allows knowledge to enter and exit the institution and therefore improve the access to innovation. It sets out that institutions need to exploit external sources of information and innovation and cannot rely only on internally generated knowledge (Chesbrough, 2003; Chesbrough & Crowther, 2006; Enkel et al., 2009).

One promising tool of OI is university-industry collaboration (UIC) for enhancing organizational capacity - where an organization employs external networks (Dess & Shaw, 2001), a complementary option to traditional internal R&D (Coombs et al., 2003). Basing on complementary resources approach, the UIC can be utilized in leveraging the competitive advantages of the engaged firms (Das & Teng, 2000). The number of firms involved in relationships with external partners, including other firms and universities, has steadily increased over the last few decades (Bellucci & Pennacchio, 2016; Jacob et al., 2000; Perkmann et al., 2011). Prior research of company-internal success factors has found that a greater openness to external ideas positively influences the innovation performance of UICs for the collaborating firms (Fey & Birkinshaw, 2005). The definition of success of the collaboration and its outcomes varies thereby between the actors in UIC (Barnes et al., 2002, S.13). Brown & Svenson (1988) defined a first process models on R&D performance framework which distinguish between four stages - inputs, process, outputs and outcomes. In several iterations, this performance framework was further developed into UIC lifecycle stages inputs, in-process activities, outputs and impacts (Barnes et al., 2002, S.13; Perkmann et al., 2011). The variety of UIC formats are considered in the inputs stage of the UIC. To measure the effectiveness of UIC and how UIC can replace or at least contribute to the R&D capabilities of a firm, objective measures were derived by (Ankrah & AL-Tabbaa, 2015) in a systematic literature and a conceptual framework developed for a greater understanding of UIC knowledge and technology exchange. Fernandes et al. (2017) linked in the UIC lifecycle stages with the program and project management lifecycle and defined indicators on basis of Seppo & Lilles (2012) and Perkmann et al. (2011) for each program management phase of funded cooperative research programs. In a recent study Albats et al. (2018) addressed the issue of non-existent universal key performance indicators (KPI) for the UIC lifecycle stages by taking in account existing studies (Perkmann et al., 2011; Piva & Rossi-Lamastra, 2013; Rossi & Rosli, 2015; Seppo & Lilles, 2012). In an extensive multiple case study design, they identified common and context-specific KPIs of UIC success at a micro level of bilateral research projects. Only in the recent study of Albats et al. (2018) and Fernandes et al. (2017) the KPI's are contextualized to specific UIC formats over the entire lifecycle. Perkmann et al. (2011) derived his framework based on a synthesis of the theoretical literature. The entire framework was not validated in an empirical way. Perkmann et al. (2011) examined UIC from a firm view as well as Al-Ashaab et al. (2011). This research aims to specifically address the empirical validation aspect of managing a performance management system during a UIC research projects. Furthermore, the suitability of the framework is challenged regarding the processes and objectives involved in university-industry interaction. All studies are strongly oriented towards exclusively the outputs (mainly measuring the university income) and not focusing on the actual knowledge transfer process. To really elaborate on the suitable KPI's for the UIC success, Rossi & Rosli (2015) propose the options to recognize that all institutions differ by their strategy, mission, goals, research areas, etc. and apply case-specific metrics or to develop a very broad set of KPIs to choose, which metrics fit best to their actual activities. By clearly defining the boundaries and use of the UIC activities in this case study, both options are contextualized on a specific case. There is a need for longitudinal research to provide additional insights into cause and effect dynamics to access the 'value' of KPIs in both short term and long term scales (Ankrah & AL-Tabbaa, 2015, S.402). To validate the impact of UIC on the R&D activities, a project- specific set of KPIs representing a micro-level which more accurately reflects the KPIs the individual stakeholders seek in through the UIC lifecycle (Rossi & Rosli, 2015) are required. To address this gap, the research focuses on context specific indicators of UIC at the micro level for the in-process activities of UIC.

This research elaborates with a long-term study UIC indicators at the operational technology management (TM) level for manufacturing technology R&D projects. The framework is prospective, reliable and multi-dimensional to access UIC R&D projects.

4.2 Theoretical background

4.2.1 Industry motivations for university-industry collaborations

UIC has its own benefits and drawback for engaged parties. Regarding benefits, several studies (e.g. Geisler, 1995; Lee, 2000) have linked motivation to benefits subsequently realized in UIC. The motivation for industry to engage in UIC R&D projects are broad. These were identified in quantitative as well as qualitative research studies. The motivations are certain and crucial to foster UIC in the industry like the engagement with high-end industrial research, sources of new knowledge and technologies, assistant in establishing technical standards, leverage of new technologies, stimulation of creativity, decrease of R&D investment, access to international cooperation networks and reduction of R&D costs (cost sharing) as well as use of university infrastructure (Caloghirou et al., 2001; Cassiman & Veugelers, 2006; Santoro & Chakrabarti, 2002; Tether, 2002; Bayona Sáez et al., 2002; Schartinger et al., 2001). These supports to reduce the impact of current shorter product life cycles (PLC) (Bonaccorsi & Piccaluga, 1994). The firm can get access to a source of new competitive technologies that render the distance between design and production relatively short (Santoro & Gopalakrishnan, 2001). This enables a quick recovery of the R&D costs of a new products, since the UIC might involve activities like development and prototyping (Ankrah & AL-Tabbaa, 2015, S.393–394). In addition, the enhanced corporate image, public relations and recruiting possibilities of highly skilled employees, creative talents are given motivators to engage in UIC for the industry. (Tether, 2002). The relationships with established and reputable institutions such as leading research universities could enhance a firm's legitimacy in the eyes of other powerful stakeholders (Hong & Su, 2013; Mian, 1997).

These collaborations playing a major part for accessing and leveraging valuable resources such as star scientists and state-of-the-art research facilities and exploiting scientific knowledge and novel inventions (Audretsch et al., 2012; Liebeskind et al., 1996; Subramanian et al., 2013). Science-based firms are levers in the generation of the economic value of scientific findings from universities (Pisano, 2010; Stuart et al., 2007) - the transformation of academic inventions into commercial technologies (Baba et al., 2009; Lavie & Drori, 2012; Markman et al., 2008). UIC is important for various stakeholders in the innovation ecosystem, especially firms, research institutions, funding organizations and policymakers (Bishop et al., 2011; Bozeman et al., 2013; Cunningham & Link, 2015; George et al., 2002). Summarized, the drivers to pursue UIC for firms are: the access to scientific competencies, ability to source innovation and ultimately to obtain competitive advantage as the result of collaboration (Bonaccorsi & Piccaluga, 1994; Dooley & Kirk, 2007; Perkmann & Salter, 2012). The cost savings, especially in the knowledge creation and exploitation (George et al., 2002), could give a firm competitive advantage and improve its financial performance (Grant, 1996).

Industry entering UIC to commercialize universities-based technologies for financial gain (Siegel et al., 2003). Many firms desire exclusive rights to the technologies that are generated. They seek to maintain control over the direction of universities research and the proprietary of the technologies (Newberg & Dunn, 2002).

Interorganizational governance mechanisms play a huge role in UIC. In the triple helix it is one force, which clearly defines the success of the UIC activities. The government is a key player in facilitating the establishment and development of such collaboration (Perkmann et al., 2011). The governments have been obligated by the global rapid changes in the competitive and technological environment to take actions to support research interactions between the universities and industries. The governments believe that universities could aid in economic regeneration via knowledge and expertise transfer in UI partnerships (Mora-Valentín, 2000; Perkmann et al., 2013). To benefit as industry from most of the governmental initiatives, industry has to collaborate with the universities (Howells & Nedeva, 2003). In this study the governmental mechanisms and boundaries are predefined in the case study. The mechanisms are static and softly affecting the indicators.

4.2.2 University-industry collaborations R&D formats and their overarching process

Important formats of UIC in R&D are bilateral contract research, consortia publicly funded research and consulting by institutes. Consortia research involves more than just one industrial firm and faculty. All these formats include knowledge and technology transfer. The knowledge transfer contains highly interactive activities like ongoing formal and informal personal interactions, and personnel exchanges. (Seppo & Lilles, 2012), with aims to recruit recent university graduates and employ student interns, co-author of research papers by university and industrial firm members. The technology transfer focuses on combining complementary contributions of the university-driven research and industry expertise to develop and commercialize technologies. (Seppo & Lilles, 2012) Often the universities provide basic and technical knowledge along with technology patent of licensing services. Industry members provide knowledge in a specific applied area along with a clear problem statement related to market or firm demand (Santoro & Chakrabarti, 2002).

4.2.3 Operational technology management

The TM consists of three levels – corporate (network view), business (external view), and operational (internal view) (Skilbeck & Cruickshank, 1997). “Corporate” is concerned with the multi business activities in respect to the world market (Perrino & Tipping, 1989). “Business” links the technological activities and market focus to ensure competitive advantages of the firm. In this area several tools were developed to manage technologies (e.g. Betz, 1993; Steele, 1989). “Operational” addresses the internal R&D and innovation management of the business (Twiss, 1992). It describes how to optimise internal processes to manage technology effectively. Phaal et al. (2001) developed based on this model a TM assessment procedure. Cetindamar et al. (2009) defined six generic TM activities: 1. Identification, 2. Selection, 3. Acquisition, 4. Exploitation, 5. Protection, and 6. Learning. Unsal & Cetindamar (2015) further developed the model of Gregory (1995), Rush et al. (2007), Levin & Barnard (2008) and Cetindamar et al. (2009) into TM routines, which distinguish between TM activities and supporting activities. TM routines are used in large firms connect strategic (macro) and project (micro) levels of analysis (Burgelman, 1983). The routines describe how work gets done and focuses more on the increasingly important resource-based view that they are sources of sustainable strategic advantage (Collis, 1994; Grant, 1996; Levitt & March, 1988). In an cluster analysis Unsal & Cetindamar (2015) elaborated three clusters of TM processes. The first cluster is the technology development cluster. The enclosed processes are mainly the technology identification, selection and acquisition processes. These are the main activities of the technology development. The second cluster is called technology exploitation and innovation cluster. The last cluster is the project management cluster. At the operational level, the technologies were internally identified, selected, and an acquisition strategy defined (Probert et al., 2000). In the exploitation activity the desired profit or other benefits can be generated inside the firm. The implementation, absorption and operation of the technologies are required to lift these benefits. Thereby two types of innovation can be achieved – radical or disruptive innovation and incremental innovation. The radical innovation can be described as ‘‘a new product that incorporates a substantially different core technology and provides substantially higher customer benefits relative to previous products in the industry’’ (Chandy & Tellis, 2000). The incremental innovations “involve relatively minor changes in technology and provide relatively low incremental customer benefits per dollar’’ (Chandy & Tellis, 1998). Incremental innovation can be easier achieved because it likely has a lower complexity of knowledge and greater shared knowledge base (Cohen & Levinthal, 1990; Lane et al., 2006). All innovation need to overcome organizational innovation constraints as no freedom for innovative thinking, rejection of ideas, and no support for innovation projects (Hölzle et al., 2018).

The success of TM is determined by the readiness and abilities of engineers to draft ideas and concepts and manage development, the time lag between the development of a technology and the commercialization of a product or service and insight into the future when making evaluations and planning (Abe, 2007). These important factors can also be applied on UIC R&D projects. The framework in this study was elaborated with insight of engineers from the draft of an idea up to the management of its development. The in-process activities provide practitioners a guideline how to evaluate and plan during the collaboration to successful shorten the time lag between the development and innovation of the technology. This study focuses on the acquisition and exploitation activities at the operational TM level.

4.2.4 Technology management in university-industry collaborations R&D projects

UIC projects are managed in a way like common R&D activities in firms. This includes creativity techniques for ideas' generation, stage gate process for project selection and continuation, road mapping and many other tools (Perkmann et al., 2011) It is crucial to define common KPIs of the UIC success. This allows better management of collaboration through continuous evaluation and thus, provides directions for improvements in the current and future collaborative initiatives (Flores et al., 2009).

The cost sharing has been identified as one of the primary motivations of interaction (Caloghirou et al., 2001; Schartinger et al., 2001; Eom & Lee, 2010). Cohen et al. (2002) report that universities and industry research can enhance firms' sales, R&D productivity, and patenting activity.

Especially in high-tech industries, (Fernández López et al., 2015, S.659) found that carrying out process innovation increases the interest in cooperation engagement with universities. University provide access to knowledge for the firms' innovations development (Bayona Sáez et al., 2002; Hall, 1993).

R&D to achieve radical and disruptive innovation is a very costly, risky and lengthy process. It is difficult and challenging for firms to innovate in short cycles to shorten the product life cycles and quickly react customer needs in an increasing global market (Flores et al., 2009, S.25). Furthermore, firms collaborate because of the rapid technological change, strong markets and high levels of global competition, complexity and uncertainty of the innovation process (Bettis & Hitt, 1995; Wright et al., 2008).

The benefits arising from external collaborations are often enhanced or undermined by the R&D focus inside the firm (Markman et al., 2008; Perkmann et al., 2013). Brehm & Lundin (2012) found that the impact of universities on sector innovation among different manufacturing sectors is contingent on the sector's investment into absorptive capacity.

A R&D measurement system contains several metrics, standards, techniques and timing of measurement and reporting (Kerssens-van Drongelen & Cooke, 1997; Kerssens-van Drongelen et al., 2000). The systems should combine both retrospective (lagging) and prospective (leading) indicators. Prospective indicators reflect the aspects of a process that are assumed to be causally related to certain desired outcomes. Measures focusing on outcomes reflect the intended outcome of a process and are very reliable (Smith, 1976). However, focusing on retrospective indicators can result in a delay of interventions to align the performance of a process (Kostoff & Geisler, 2007).

The evaluations, if the knowledge exchange with and the fresh perspective of academia can replace or at least contribute to the R&D capabilities of the firm, are still unresolved. A valid research outcome in this direction critically affects the decision making regarding the investment in UIC by the firm. (Ankrah & AL-Tabbaa, 2015, S.402) For the knowledge exchange phase (in-process activity) the study selects important indicators for manufacturing technologies.

Albats et al. (2018) identified in several case studies common measures for each phase of the UIC lifecycle.

- Input: Dedicated resources to manage the collaboration process, partner working hours allocation and share of non-governmental funds.
- In-process: Level of efficiency in managing collaborative process and clarity of in the division of responsibilities.
- Output: Publications and companies introducing product/process, marketing or organisational innovations.
- Impact: New strategic partners and change/renewal of business revenue structure.

Furthermore, the study named case specific measures, which are understudied in the UIC literature, like the change in the environmental impact, development of mutual innovation pipeline, firm image improvements, number of calls for collaboration from new partners, the amount of knowledge acquired by the firm, and the increase of firm's competitiveness measured by the change in the volume of export and increase of production volume caused by the results of the joint R&D (Albats et al., 2018, S.414).

Indicators and milestones for UIC success assessment are already required in the input stage. This provides information to track experiences in established collaboration and minimize the confusion, conflicts of interest in the project implementation. (Albats et al., 2018, S.397)

Important input indicators are the collaborators' resources - time, budget and staff allocated to collaboration, the total R&D expenditure (Allen et al., 2007; Perkmann et al., 2011; Seppo & Lilles, 2012; Tijssen et al., 2009). The capabilities of the collaborators are defined by the number of publications, citations, patents, projects or contracts in the research area (Abramo et al., 2011; Perkmann et al., 2011; Kauppila et al., 2015), as well as the number of conferences hosted or participated in (Al-Ashaab et al., 2011). The firms' capabilities could be also assessed by quality certificates (ISO), membership of association or research group, employees occupation and education (Seppo & Lilles, 2012). The corporate strategy should include UIC and an amount of resources dedicated to support UIC (Kauppila et al., 2015), moreover the perception of the benefits from UIC and existing ties, e.g. strategic partners, alumni, lectureships, previous collaborations (Seppo & Lilles, 2012). The needs, benefits, and communication channels have to be mutually defined and explored (Barnes et al., 2002; Plewa et al., 2013; Thune & Gulbrandsen, 2014). The importance of the geographical proximity of the partners needs to be clarified for the particular collaboration (D'Este et al., 2013; Laursen et al., 2011; Petruzzelli, 2011).

Bstieler et al. (2015) illustrated that a shared governance of UICs by firms and universities contributes to the trust between the partners and allows responding to changes in the project environment in a coordinated and mutually agreed way. The joint planning, responsibility, evaluation and adjustment of the project help prevent misunderstandings and promote effective teamwork not only in R&D collaborations between firms (Asmus & Griffin, 1993; Lawson et al., 2009) but also in UICs (Bstieler et al., 2015, S.118). In trusted collaborations, firms can absorb more scientific knowledge and tend to achieve better innovation performance.

The length and basic research orientation of publicly funded R&D projects can lead to impatience with the collaboration progress by the firm as university researchers are usually less affected by timeliness and financial bottom lines than their corporate counterparts. (Bstieler et al., 2015, S.119)

The outcome of UIC is normally evaluated by industry or universities actor's posteriori, comparing prior needs and expectations and actual or perceived satisfaction. The actors may vary in definition of the success of the interaction and its outcomes (Barnes et al., 2002). Adding quantitative data to the evaluation like the number of new patents, products, publication can reflect the real value of the UIC and justify its cost and risk (Ankrah & AL-Tabbaa, 2015, S.401).

4.2.5 Manufacturing technologies & their readiness levels

Firms are facing a multitude of challenges like justification of investment decisions, conflicting objectives, or lack of knowledge of the benefits (García A & Alvarado I, 2013), when choosing and implementing advanced manufacturing technologies, defined as any equipment or methodology that is part of the production system for improving performance (Chuu, 2009). Consequently, not only at the strategic level the assessment and selection of manufacturing technologies is crucial in order to assure the competitiveness of a firm (Phaal et al., 2004). The production processes and manufacturing systems technologies are linked to the product context (Phaal et al., 2006). They are the key drivers for cost reduction (Schuh et al., 2014) and process efficiency (Klocke et al., 2014) as well as product functionality improvement by enabling new product features e.g. by 3D printing of components.

The Manufacturing Readiness Level (MRL) is a procedure developed by the United States Department of Defence in 2005. It is a method used in the industrial environment with quantitative measures to assess the maturity of a manufacturing technology. The two main risk areas are immature product and manufacturing technologies. The technology readiness level (TRL) and the MRL, which are used to measure and point out those risks, collaborate with each other. An MRL for example always requires a nominal level of the technology readiness. There are ten MRLs which correlate to the nine TRLs. MRL 1 to 3 are attached as a group in Conceptualization, MRL 4 to 6 together as Technology Development and MRL 7 to 10 collectively in the Development and Product Deployment (OSD Manufacturing Technology Program, 2016). A project can be assessed for an MRL when doing an MRL review process. For a correct assessment, MRL criteria and categories have been defined by the OSD Manufacturing Technology program. The categories are as follows: 1. Technical - Primary Technical Objective, Manufacturability, Cost, Yield and Rate, Quality Management and Industrialization. 2. Project Management - Implementation Plan, Business Benefit and Intellectual Property. For the accomplishment of an MRL, all categories need to fulfil the specific level criteria.

4.3 Research methodology

This study is a longitudinal case study with an abductive reasoning approach. It observed over two years UIC manufacturing technology R&D projects between a German university and German large high-tech firm. The examination of what are important indicators of the operational TM, which affects the collaborations between universities and industry constitutes the empirical part of this paper. The abductive approach was used to elaborate indicators for the UIC lifecycle stages in-process activities and outputs. The literature was reviewed to identify existing indicators of these stages and tested the theories in our empirical context. Therefore, interviews with five PhD students, responsible for manufacturing technology R&D projects were executed four times in the two years period. All projects were executed in an identical collaboration framework. The semi-structured interviews were fully transcribed, coded, and detailed indicators for each project elaborated and allocated to the UIC lifecycle stage in-process activities and outputs of Perkmann et al. (2011). Evaluation coding by magnitude and sub coding to emerge categories out of the data were conducted. The derived factors out of the theory were overlapped with the emerged categories to validate the existing indicators and identify novel indicators. In the second cycle of coding a longitudinal coding was executed, and a summary matrix created to build a framework of indicators for UIC manufacturing technology R&D projects. Internal review documents illustrating the progress of the projects were studied to evaluate the success of the collaboration. Triangulation was used to overcome the limitations of case study research through data from a variety of sources. He acknowledges the limited generalizability of results coming from selecting case study as a method. Additionally, to the interviews and review documents, observations in meetings and other events generated further data. The insights that resulted from unanticipated data contributed to further development of the framework and triggered the search for corresponding theoretical concepts.

4.3.1 Abductive approach and research process

In this longitudinal case study, three research methods were applied: qualitative interviews, document analysis, and participative observation in order to identify suitable indicators to measure the success of collaborative university-industry R&D funded projects. The abductive reasoning approach is a combination of deductive and inductive approaches. It constant moves from the empirical to theoretical dimensions of analysis (Dubois & Gadde, 2002). Lukka & Modell (2010) state abductive is gradually accepted as an important part in interpretive research. The process starts with ‘puzzles’ and the research process is devoted their explanation (Bryman & Bell, 2015). A matching between theory and reality is done by going back and forth between framework, data sources, and analysis. This could not be done by purely inductive or deductive approach (Kakkuri-Knuuttila et al., 2008b, 2008a). In this study, a general framework was developed and applied based on Perkmann et al. (2011) at the operational technology level management level of UIC R&D projects. Some of the evidence does not fit in this framework. Therefore, a literature review is needed to explain the new findings. The second step of the abductive approach is the direction and redirection. It focuses on using more than one source of evidence to discover new dimensions of the research problem. The direction of this study is influenced by the theory, the literature review, and exploratory longitudinal case study. Exploratory case studies aim to find answers to the questions of 'what' or 'who'. The data collection method is often accompanied by additional data collection methods such as interviews. Case studies can capture complexities of real-life situations so that phenomenon can be studied in greater levels of depth.

The abductive approach address weaknesses associated with deductive and inductive approaches like the lack of clarity in terms of how to select theory to be tested via formulating hypotheses in deductive reasoning and "no amount of empirical data will necessarily enable theory-building" (Saunders et al., 2012) in the inductive reasoning. It overcomes these weaknesses via adopting a pragmatist perspective. The stages of the research process are illustrated in Figure 4-1. Initially, the unstructured interviews were conducted first, and the theory was screened for UIC and TM frameworks. Then the match of theory and evidence helped to direct the research. After 9 months the cases evolved, and second semi-structured interviews were conducted. The first and second interviews were coded to derive further evidence of the empirical data. Additional theory was screened for UIC indicators and R&D performance methods. Then the match of theory and evidence helped again to direct the research. After 6 months the cases further evolved, and third semi-structured interviews were conducted. The interviews were fully transcribed, and a structural coding approach, along the lines of Krippendorff's (1980) recommendations, were utilized to emerge categorization. The previous interviews were also categorized. Literature about UIC indicators and TM measures were added based on the emergent categorization. After 9 months the cases further evolved, and fourth semi-structured interviews were conducted. The interviews probed into three themes, which reflect the purpose of the paper, and these in turn therefore constituted the main sections of the interview guide: (1) Technology and current progress (2) Questions addressing two phases of TM activities: (a) Acquisition (Planning & Development): budget, resources, network, communication, maturity (b) Exploitation: knowledge transfer, competitive impact (3) The overall cooperation within the relationship. All interviews were coded based on the relevant theories and literature and a core categorization was derived. These were utilized to define the final framework of the study. The PhDs were observed since the beginning of the program (October 2016), in naturally occurring situations, namely during regular management and technical meetings and analysed internal MRL reviews documents. Therefore, through participative and systematic observation, it was possible to realize and perceive the collaborative university-industry R&D context and identify the key TM practices for this context.

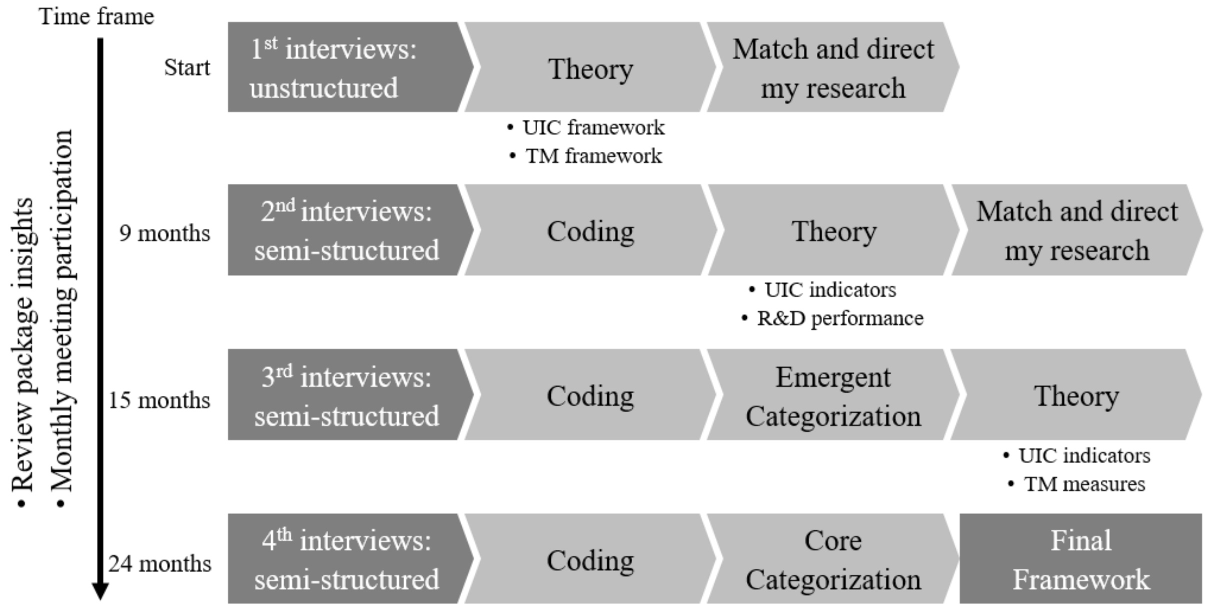

Figure 4-1: Research process of the abductive approach in an exploratory case study (Own illustration)

Influencing factors of the research process are the theory, boundaries in the empirical world, framework and the evolving case (Saunders et al., 2012). The literature review helped to find the research gaps. By engaging with the case, the boundaries of the empirical world were adopted on the relevant literature and theory. The boundaries in the empirical world were defined with the help of the theory, where the framework enabled to link the theory and the evidence. Empirical findings as well as the literature guided the research. The evolving case is a 'tool' because the case evolves during the study to a 'product'. The data from the case are the pieces of a puzzle. The research design was chosen because of the limited knowledge how the in-process activities in UIC R&D projects can be connected with the operational TM and what are the important indicators in the joint R&D activities for manufacturing technologies from the industrial perspective.

4.3.2 The case-study – Centre of Excellence at the University Campus

The case represents a five-year publicly funded manufacturing technology R&D program between a German university and German large high-tech firm (Centre of Excellence at the University Campus). The program is one aspect of the collaboration of the firm and the university. The firm's collaboration portfolio also includes a strategic partnership program, many ongoing and completed bilateral and publicly funded R&D projects, lectureships, memberships and OI formats with the university. The studied program consists of five topic areas, which were jointly drafted and submitted to the national funding authority. As per conditions of governmental grant, the firm is funding the half of the total project budget - it specifically focuses on commercializing the research results and thus, receives the profit. The firm is subcontracting the involved institutes of the university in the program. The budget per institute is clearly defined in the grant statement. Thereby, each topic area has his own governance and control mechanisms in place. Every quarter of the year the progress of both stakeholders (firm and university) must be reported to the funding authority. If the timeline or work packages of a topic area must be adjusted, the funding authority must approve it in the quarterly steering committee. A team of one PhD student in the firm and PhD students at the institute are allocated to the work packages of each topic area. All students are located at the campus of the university. Thereby, a geographical proximity of the researchers is given. The firm PhDs travel on a regular basis to the main factory of the business unit. Due to the location of the factory (East Germany) and the university (West Germany), the business trip to the main factory must be planned and with a clear purpose. The business trips are utilized to transfer the generated knowledge and developments into the firm processes and to identify new requirements of the real business cases. The Figure 4-2 illustrates the framework and boundaries of the case study. The R&D performance of the projects were analysed over the period of two years. Here, the MRL assessment tool was used with the R&D project lead. The assessment was executed for each reached MRL level of the R&D projects. With the mixed-method approach, qualitative and quantitative methods were assigned with a clear structure to our research process. The indicators identified in the case study point to important issues for further investigation.

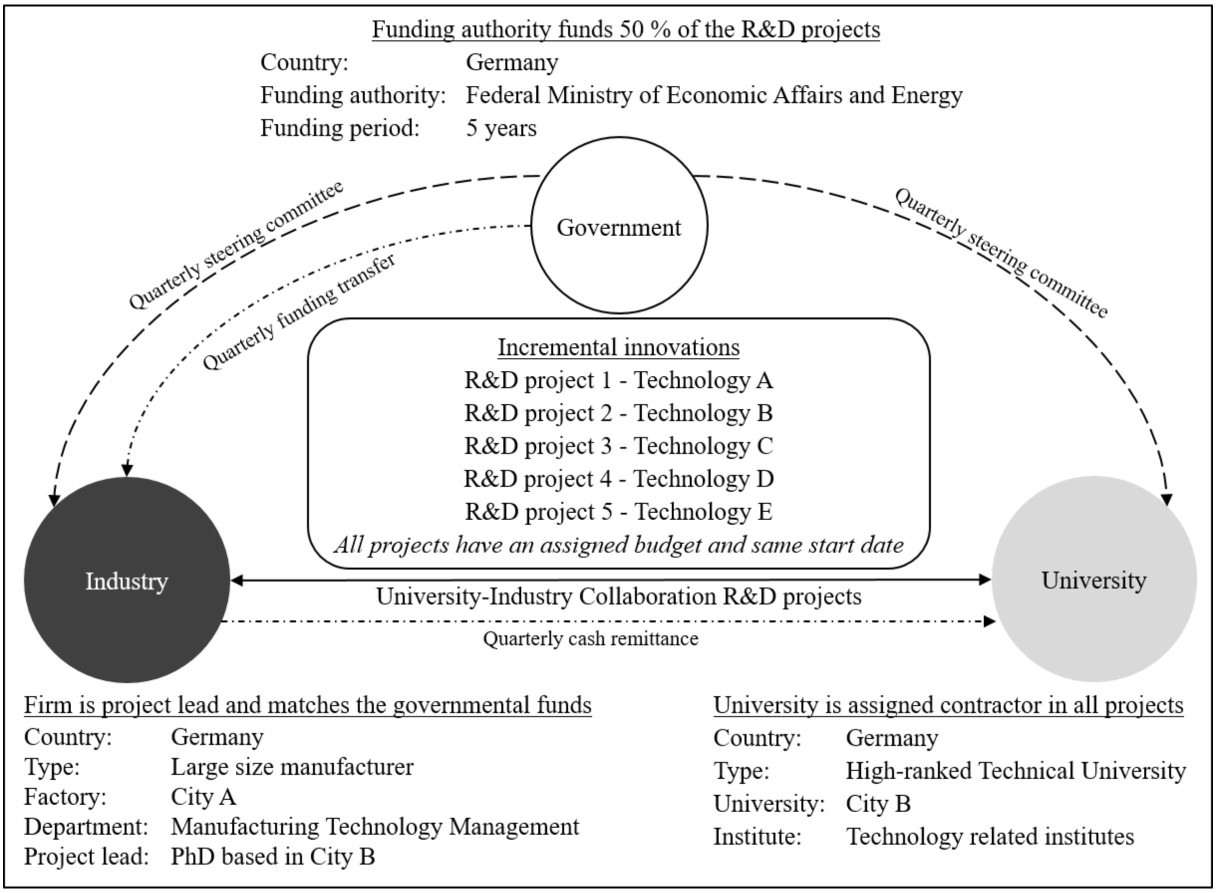

Figure 4-2: Framework and boundaries of the case study in the triple helix of Etzkowitz & Leydesdorff (2000) (Own illustration)

4.4 Empirical findings

In order to obtain suitable indicators for UIC R&D projects at the operational TM level, it is necessary to connect UIC and TM processes and derive important indicators for this new process. Therefore, the link of UIC and TM processes is first described in this specific area based on the theory part of the study. In detail, the core categorizes, and important indicators based on the qualitative data are integrated into the process and the complete final framework is shown in detail. The MRL assessment of the UIC R&D projects provides at the end of the empirical findings a first hint about the progress of the evolved case.

4.4.1 University-industry collaboration and technology management process link

To link the UIC lifecycle stages with the TM procedures, literature was reviewed of existing UIC and TM frameworks. Over the time of the study the framework evolved until the last interview. New arising indicators in the coding procedure were detected in the literature or defined as emerged indicators of the study. All indicators were assigned to a specific phase of the final framework. The final framework is shown in Figure 4-3. The UIC lifecycle is based on

Perkmann et al. (2011). It implies four stages of UIC and its assessment: inputs, in-process activities, outputs and impact. The output implies more tangible and direct or ‘hard’ results and impact mean less tangible, ‘softer’ effects of collaboration coming possibly later in time. The in-process activities were further divided in this study into in-process Planning and in-process Development activities. The lifecycle was selected considering similarity of objectives and robustness. Indicators of Barnes et al. (2002), Seppo & Lilles (2012), Ankrah & AL-Tabbaa (2015) and Fernandes et al. (2017) were added and assigned to the lifecycle. The procedure of Nielsen et al. (2013) and Fernandes et al. (2017) to link an internal Program and Project Management lifecycle with the UIC lifecycle was transferred on this study. The TM framework is based on the TM procedures of Gregory (1995), Rush et al. (2007), Levin & Barnard (2008), Cetindamar et al. (2009), and Schuh & Klappert (2011). The firm applied this specific TM framework in the analysed UIC R&D projects. The framework consists of five subsequent TM activities and two parallel activities. All subsequent activities have a fluent transition and allowing the overlap of activities. The input of the collaboration is pre-defined. This means the technology is already identified and selected by the partners in the collaboration. Budget and resources are allocated based on the grant statement. The in-process planning is considered as the technology acquisition. The in-process development is still part of the technology acquisition, but the readiness of the technology already allows to exploit it inside the firm and university. The output is the fully utilized technology exploitation. The exploitation normally goes hand in hand with the protection, due to the OI approach multiple stakeholder already exploiting the technology during their development. The joint protection (e.g. invention disclosures) started during the acquisition. A specific protection strategy is executable at the end of the funding period. The entire study focuses on the in-process activities (technology acquisition, exploitation, evaluation and supporting activities) and partly the output of the UIC R&D project.

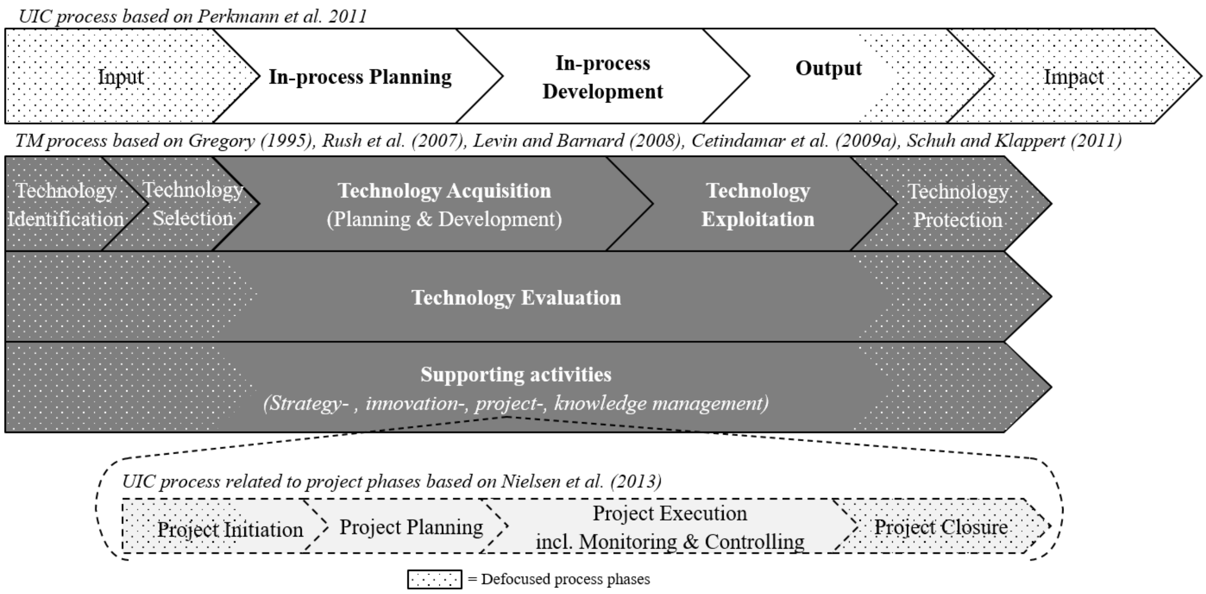

Figure 4-3: Link of UIC and operational technology management framework

The focus was defined due to existing setup of the case. In general, the literature clearly is too much oriented towards exclusively the outputs (mainly measuring the university perspective) and not focusing on the actual knowledge transfer during UIC. Rossi & Rosli (2015) recognised that all institutions differ by their strategy, mission, goals, research areas, etc., so that case-specific metrics or a very broad set of indicators are required to allow institutions to choose, which metrics fit best to their actual activities. This study aims to broaden the set of indicators for manufacturing technology UIC in R&D projects.

4.4.2 Indicators for manufacturing technology R&D projects

Main categories to facilitate or impede UIC are the capacity and resources, legal issues and contractual mechanisms, management and organizational issues, issues relating to the technology, social and other issues (Ankrah & AL-Tabbaa, 2015). These indicators were validated in several literature (Bruneel et al., 2010; Cricelli & Grimaldi, 2010). The variety of indicators confirms Barnes et al.'s (2002) view that the success of a collaborative project is influenced by a complex interaction of indicators. If the indicators were correctly managed, the positive effect on the observed success of knowledge and technology exchange was found as well as if the same indicators were mismanaged, a corresponding negative effect on the observed success of knowledge and technology exchange were presented (Ankrah & AL-Tabbaa, 2015). Siegel et al. (2003) already stated that organizational and managerial issues are main critical indicators in the success of the relationship between university and industry.

Appendix 2 illustrates main process components of the entire collaboration. Below, the validation of existing indicators and new indicators derived out of the case study is described.

4.4.2.1 Validation of existing indicators – Defocused UIC R&D project phases

Input indicators

The input phase itself was not analysed in the study. However, the dedication of resources to manage the collaboration process (Albats et al., 2018) affect the collaboration and thereby subsequent process. The semi-structured interviews allowed the interviewee to interpret and answer the questions in a broader sense. This enabled to derive important affecting indicators of this phase for the UIC R&D projects. The partner evaluation indicators of Barnes et al. (2002) as mutual understanding of benefits and importance of collaboration, complementary aims, acknowledgment of expertise and strengths help the firm to choose the right partner for the UIC R&D project. An existence of innovation policy (Fernandes et al., 2017) at both parties build the foundation to start the UIC. The assignment of equally matching collaborators' capability (Fernandes et al., 2017) like degree of master, postgraduate, PhD in team (Barnes et al., 2002) and experience in UIC (Seppo & Lilles, 2012) of the team support the mutual respect and trust in the project. Furthermore, it enables the team to recognize arising opportunities or challenges in the UIC R&D projects (Iqbal et al., 2011). The funding and resources like R&D expenditure and budget are the final leveraging indicators of the input phase (Perkmann et al., 2011; Seppo & Lilles, 2012).

Impact indicators

The analysed case included pre-conditions. The case is one aspect of the collaboration of the firm and the university. The firm's collaboration portfolio includes ongoing and completed UIC R&D projects with university. It exists a long-term relationship with the partner. One of the most important impact indicators is accordingly the partner sustainability, which can be seen as the value of new collaborative research projects generated (Fernandes et al., 2017). Thereby, the case itself is already one success factor for the overall UIC.

Output indicators

The output indicators and input indicators are the main indicators presented in the literature. They are especially useful to evaluate the overall UIC performance of a firm or university in a quantitative way. The number of new products, new process improvements, new solution concepts, new project ideas or student placements in industry can be easily collected and evaluated with available access to the data. Comparing these with input indicators (e.g. budget) enables statements about the success of the UIC R&D projects. In this study, the output phase was only partly observed. The link of UIC with the TM processes including MRL reviews facilitated to also identify output indicators in this study. The main category innovations include the number of new process improvements (Fernandes et al., 2017; Perkmann et al., 2011) and improved innovative ability and capacity to keep up to date with major technological developments for the firm. The solution concepts category includes increased MRLs and thereby increased TRLs (Fernandes et al., 2017; Perkmann et al., 2011). As an effect, the firm immediately improves its competitiveness (Ankrah & AL-Tabbaa, 2015). Through participating in the monthly meeting and accessing the review packages, drawback indicators such as the results in theoretical and impracticable solutions ("Cultural Gap", the university staff too theoretical; industry's focus too much problem centred on critical situations) were measured and the risk of incomplete transfer or non-performance of technology (Ankrah & AL-Tabbaa, 2015). The intellectual property (IP) management in the TM procedure was already a topic during the development phase. Some IP was not shared with the university, leading to a complete cancellation of one subproject.

4.4.2.2 Validation of existing indicators – Focused UIC R&D project phase

The focus of the study lies on the in-process activities phase. Table 4-1 illustrates the measured indicators of the existing literature. The clear spotlight on the executer of this phase, namely PhD students in this case study, facilitated to analyse the mechanisms of this phase in depth.

Table 4-1: Measured indicators in the UIC R&D in-process activities phase (Own illustration)

<table>
<tr><th>UIC & TM Phase</th><th>Process component</th><th>Indicators</th></tr>
<tr><td rowspan="5">In-process planning

Technology Acquisition (Planning)</td><td rowspan="4">Project planning</td><td>• Project charter with clearly defined objectives & responsibilities (Barnes et al., 2002)</td></tr>
<tr><td>• Mutually agreed project plan with milestones (Barnes et al., 2002; Besner & Hobbs, 2012)</td></tr>
<tr><td>• Realistic aims (Barnes et al., 2002; Paula & Silva, 2017)</td></tr>
<tr><td>• High level project scope plan - fit into R&D technology strategy (PMI, 2017)</td></tr>
<tr><td>Governance establishment</td><td>• Joint governance model setting (Barnes et al., 2002; Chiesa et al., 2009)</td></tr>
</table>

Table 4-1: Measured indicators in the UIC R&D in-process activities phase (Own illustration)

UIC & TM Phase	Process component	Indicators
In-process development Technology Acquisition (Development)	Project execution	• Adequate resources (funding, human and facilities) (Barnes et al., 2002)
		• Regular progress monitoring with progress reports - Steering committee, progress and technical team meetings (Barnes et al., 2002; Besner & Hobbs, 2006)
		• Dissemination and communication plan for effective communication (Barnes et al., 2002; PMI, 2017)
		• Ensuring collaborators deliver (Fernandes et al. 2017; Nielsen et al., 2013; Silva et al., 2018)
		• Re-baselining (Besner and Hobbs, 2006; PMI, 2017)
	Commitment	• Treatment of confidential and proprietary information (Barnes et al. 2002)
		• Teamwork and flexibility to adapt (Ankrah and AL-Tabbaa 2015)
		• Mutual trust (and personal relationships) (Barnes et al. 2002)
		• Training of technology transfer staff (Perkmann et al., 2011; Seppo & Lilles, 2012)
	Expertise & Availability	• Access to leading edge technologies or new knowledge and/or a wide variety of multidisciplinary research infrastructure or research expertise (Ankrah and AL-Tabbaa 2015)
		• Access to specialized consultancy, solvers of technical problems (Ankrah and AL-Tabbaa 2015)
		• High educated team members - Master and PhD degrees (Seppo and Lilles 2012, Perkmann et al. 2011)
		• Joint publications (Fernandes et al. 2017; Perkmann et al. 2011)
		• Applied research (Perkmann et al. 2011)

Table 4-1: Measured indicators in the UIC R&D in-process activities phase (Own illustration)

UIC & TM Phase	Process component	Indicators
In-process development Technology Acquisition (Development)	Technology transfer & adaptation	• Product testing with independent credibility in testing (Ankrah and AL-Tabbaa 2015)
		• Result sharing events (Fernandes et al. 2017)
		• Joint supervision of Master's degree dissertations by academic and industry personnel (Ankrah and AL-Tabbaa 2015)
		• Joint publications (Fernandes et al. 2017; Perkmann et al. 2011)
		• Applied research (Perkmann et al. 2011)
	Network & Communication	• Communications by voice/mail/email/ conference calls (formal or informal) (Ankrah and AL-Tabbaa 2015)
		• Geographic proximity (D'Este et al., 2013)
		• Workplace meetings - social contact (Fernandes et al. 2017)
		• Human capital mobility/personnel exchange (Ankrah and AL-Tabbaa 2015; Seppo & Lilles, 2012)
	Main issues	• Differing priorities/timescales (Barnes et al. 2002)
		• Role of lead researchers at the university and the firm (Barnes et al. 2002)
		• Corporate stability (Barnes et al. 2002)
		• Nature of the technology/knowledge transfer loses (Ankrah and AL-Tabbaa 2015)
		• Low level of awareness of university research capabilities (Barnes et al. 2002)
		• Leadership/Top management commitment and support (Ankrah and AL-Tabbaa 2015; Barnes et al. 2002)

Described indicators as the equality of power/dependency (Barnes et al., 2002) were not measured in the study. The project leader A explained the non-existence:

> *"We are the customer. We define what they must do, and we pay them. In the project we collaboratively execute them with the institute. But it is also a kind of contract research, which we order and supervise." (Project lead A)*

This example clearly illustrates the necessity of context-specific indicators of UIC.

4.4.2.3 Discovered indicators – Focused UIC R&D project phase

Table 4-2 illustrates the discovered indicators in the study, which were not listed in the literature of in-process activities of the UIC lifecycle stages. Appendix 3 shows some of the analysed quotes of the interviews.

Table 4-2: Discovered indicators in the UIC R&D in-process activities phase (Own illustration)

UIC & TM Phase	Process component	Indicators
In-process Development Technology Acquisition (Development)	Project execution	• Recheck responsibilities and workload allocation
		• Implement stakeholder management activities
		• Shift as many development steps as possible into the digital world – detached from production capacities
	Expertise & Availability	• Agility and flexibility in access to resources
	Technology transfer & adaptation	• Execute technical and steering committee meeting to monitor transfer & adaptation – apply MRL reviews
		• Lift direct benefits by focusing on long hanging fruits of firm processes in the transfer steps
		• Increase direct communication with the end users
		• Allocated similar technical systems at both partners
		• Include supplementary OI approaches
		• Specify clear hand over after technology development (MRL6) to the end users for implementation on the shop floor

The progress of the UIC in R&D projects was constantly measured via technical reviews & steering committee meetings. In the context of co-located researchers (project lead at university and not in the application plant), these monitoring measures were particularly important to adjust and optimize the technology acquisition for the firm.

The role of lead researchers at the university and the firm (Barnes et al. 2002) must be clearly defined in the project execution. This must be rechecked and aligned throughout the technology development.

Changing interests of all stakeholders in the projects require stakeholder management activities. These activities need to be routine task of the project leader.

The technology development should focus on low hanging fruits of firm processes in the first place to lift direct benefits and thereby gain trust and support of the entire setting. Thereby, also the issue of low level of awareness of university research capabilities in the firm (Barnes et al. 2002) is addressed.

There is a constant need for agility and flexibility of resources. In this way the technology development can clearly be accelerated.

To address the nature of technology/knowledge transfer loses, direct communication with the end users of the technology is required to include them in the development.

The technology development is detached from real production slots. For some technologies is furthermore shifted into the digital world. The technical systems should be similar at both partners.

Internal forces must be aligned in the firm. The post-project support and transition plan requires a clear hand over of the developed technology into the shop floor for implementation.

The utilization of supplementary OI approaches to enhance the development should be evaluated for each UIC R&D project and receive top management awareness/support)

The physical distance of the cities was mentioned several times in the interviews. A localization of the institutes and application plant in one geographical setting would improve the R&D processes by the direct access to and communication with the shop floor as well as shorter processes – e.g. faster rapid prototyping with real production equipment, trust building by direct connection of researchers with the workers (end users).

4.4.2.4 MRL as measure for one explicit indicator

Appendix 4 illustrates the progress of the MRL levels of the developed projects, and the number of students involved in the development. Many students of project B were acquired via an OI student challenge, which had received additional management support. This implicates that the use of supplementary OI approaches help to accelerates the development of manufacturing technology in UIC R&D projects.

4.5 Discussion and conclusion

4.5.1 Theoretical implications

UIC is a crucial factor in enhancing firms' innovation and competitiveness. The present study aimed to elaborate UIC indicators at the operational TM level for manufacturing technology R&D projects. The abductive approach allowed to develop an UIC indicator framework at the operational level of the UIC lifecycle for manufacturing technology R&D projects by linking TM procedures of a firm contextualized with a specific UIC format (Rossi & Rosli, 2015). The framework was empirically elaborated considering processes and objectives involved in the UIC interaction. The researcher reconciled the theory with the empirical context by incorporating novel indicators.

Obtained indicators from the literature of the framework were empirically tested in the case study. This provided implications about the reliability of existing frameworks. The empirical study addressed the need to confirm the appropriateness of the indicators and specify the indicators of different types of cooperation more precisely (Seppo & Lilles, 2012; Barnes et al., 2002). The researcher validated the performance management system during UIC R&D projects and utilized the results to adapt the elaborated framework.

Previous studies mainly focused on the inputs, outputs, and impact stages of the UIC lifecycle. This study is the first study, which particularly addresses the in-process activities of the UIC lifecycle stages. The qualitative approach enabled to derive new indicators for this stage in a specific environment. The stage focus reflects the indicators which the individual stakeholders more accurately seek in this UIC lifecycle stage. The longitudinal and in-depth nature of this study provides interesting contribution to the UIC literature at the operational TM level and their cause and effect dynamics in short term and long term scales (Ankrah & AL-Tabbaa, 2015, S.402). The internal firm mechanisms such as the direct connection with the end users are significant mediating mechanisms to gain benefits from cooperation with universities. To the best of the researcher's knowledge, an abductive approach with the focus on the in-process activities of UIC R&D projects has not been published yet. This indicates that the findings, based on a qualitative research study, present new contributions.

The diverse increase of maturity readiness levels of the manufacturing technologies during the in-process development activities/technology acquisition illustrates that important indicators like supplementary OI approaches, agility and flexibility in access to resources and clear responsibility hand-overs are crucial for the success of manufacturing technology UIC in R&D projects.

4.5.2 Managerial implications

This research has important implications for practice. In recent decades, governments have dedicated increasing resources to supporting research collaborations between firms and universities, based on the assumption that technology transfer will occur. Firms should include UIC R&D projects into their TM processes to fully benefit from interactions with universities. Project management procedures alone are not enough to maximize the benefits from UIC R&D projects. Due to the intense collaboration in the case study, the technology maturity level was significantly increased in the two years. Several mechanisms had to be in place during the development process to keep the progress and to justify the efforts and expenses of the activity inside the firm. The study describes these mechanisms over the UIC in-process activities and clearly illustrates what indicators impact the UIC R&D projects at the operational TM level. The progress of the technologies is causally linked with indicators like adequate resources, teamwork, training, roles, re-baselining, applied research, access to leading edge technology and clear hand overs etc. The study gives insights into the mechanisms of UIC R&D projects and its indicators. It will provide practitioners know-how to setup UIC R&D projects for manufacturing technologies to increase the innovation funnel of the firm and sustain competitive advantages.

4.5.3 Limitations and future research

This study has expanded knowledge about the UIC lifecycle stages, but it also has some limitations that call for future research. The existing literature on UIC lifecycles and TM procedures has emphasized the importance of indicators to measure the success of firms, but also other theories and interactions may also be important in-process activities of UIC. The case study only enabled to derive context-specific indicators and not common indicators for UIC in-process activities.

The research design suggests that the results should be generalized with caution. In choosing a case study approach, the researcher acknowledges the limitations of low generalizability and context-specificity. The sample for the empirical analysis was specific, although alternative configurations of the model were considered and tested during the abductive reasoning approach, this could limit the external validity of the analysis.

The analysis also used data from only one region of Germany, and only one sector. Empirical research efforts are required with different set of participants, including middle level managers, researchers, and shop-floor employees (Unsal and Cetindamar, 2015). Further investigation of other technology-intensive sectors, and different regional and national contexts, might help to develop a more robust picture of the framework and indicators.

Despite these limitations, the researcher believes that the analysis provides an empirical verification that was previously lacking in the literature on in-process activities in university–industry collaborations. An important indicator, if the UIC R&D projects are more cost-effective than similar in-house R&D project, could not be validated in the study. This needs to be elaborated in future research. Furthermore, additionally theories of quality management, which significantly leads to business performance improvements (Solis et al., 1998), could be included in the framework. The results add to understanding about how firms can manage UIC in R&D projects with external partners to maximize their benefits.

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5 Synthesis

5.1 Main results, contribution, and conclusion

The overall goal of this dissertation is to create a new (technology management-driven) perspective on open innovation (OI) and provide insights on how it can be used in a manufacturing environment. The overriding research question "How do OI formats impact the R&D activities of manufacturing technologies at the operational technology management (TM) level?" will be answered through three sub-research questions within a clearly defined setting.

The setting for this dissertation is a case study in a very large German high-tech firm. I, as the author, was embedded in an R&D unit within the operational TM department for manufacturing technologies. Thereby, I had direct access to all internal data (project-related, technology-related, financial-related, etc. documents). Furthermore, I pursued my own manufacturing technology development project inside the firm. Thus, I was able to gain first-hand experiences of activities at the operational TM. Furthermore, I was able to immediately apply and test the scientifically developed models of this dissertation in an industrial environment.

I used a deductive approach for the model development and an abductive reasoning approach to create new insights and a better understanding of OI in a manufacturing perspective. The literature on OI and TM has abundantly referenced the need to mitigate the knowledge gap regarding in-depth understanding of OI on the project level in firms as well as the connection of OI to appropriate (management) concepts and other industry fields (Kirschbaum, 2005; Laursen & Salter, 2006; Lichtenthaler, 2008; Kleemann et al., 2008; Perkmann et al., 2011; Chesbrough & Brunswicker, 2013; Piva & Rossi-Lamastra, 2013; Chesbrough & Brunswicker, 2014; Ankrah & AL-Tabbaa, 2015; Bstieler et al., 2015; Unsal & Cetindamar, 2015; Rubera et al., 2016). The growing conceptual and empirical literature on OI calls for clear guidelines concerning the best way to apply these methods at the operational level. Thus, it is both necessary and promising to conduct research on OI formats linked with TM to strengthen empirical evidence, provide structure and outlook as well as to manage the interaction of methodologies in the rising research field of resilient and adaptable innovation ecosystems.

The key results of the dissertation are threefold and contribute to expectations regarding originality and significance (Lovitts & Wert, 2009). The results are first, theoretical results (i.e., a new perspective of operational TM in combination with OI); second, methodological results based on novel R&D evaluation procedures and indicators in the technology and innovation (management) research; and third, empirical results based on new insights and propositions that promote a better understanding of OI in the manufacturing area. Each key result makes clear contributions to the existing literature and several related conclusions are drawn in a stepwise manner.

5.1.1 Crowdsourcing for manufacturing technologies

The first research question analyses the impact of OI formats at the operational TM level in technology identification, selection and acquisition: “How does crowdsourcing (CS) accelerate the R&D of manufacturing technologies at the operational level?”. A first glance of the impact of this OI format on R&D of manufacturing technologies is shown by elaborating an evaluation process for CS initiatives and connecting this process with the manufacturing readiness level (MRL) stage gate process of manufacturing technologies.

The last CS process phase is the use phase. The use phase focuses on the implementation and deployment of the ideas in the firm (Gassmann, 2013). The article analyzes this phase in detail to outline the acceleration of time-to-market of the manufacturing technologies. The generated ideas are analyzed and selected according to the following six factors: manufacturing technology readiness level, development status, risks and problems, benefits, structure and resources. To obtain an appropriate support for evaluating CS initiatives it is important to share a common understanding of the overall process. In the following the main tasks of CS initiatives over the entire process are summarized following the CIPP model. Transferable tasks are described based on qualitative and quantitative data of the initiative.

- Preparation: Define problem identification, solution strategy, concept – Purpose of the case; Define stakeholder groups and their needs and objectives.
- Initiation: Formulate problem and question; Schedule and plan procedure; Staff responsibilities; Develop process criteria; Fix and assign goals to each step of the initiative; Broadcast initiative and problem description to the crowd.
- Development: Track submitted ideas and/or solutions; Support idea refinement; Check goals achievement (e.g., number of registered/attending participants, amount and quality of submitted ideas); Review submitted ideas; Evaluate ideas and deliverables; Select winner.
- Use: Implement and utilize the ideas and results in manufacturing or further develop the ideas; Check goal achievement (e.g., number of new employees, implemented ideas and impulses for new projects).

The described tasks are a glimpse of the overall tasks in a CS initiative. They are not comprehensive (e.g. marketing as well as the legal frame are additional particularly important tasks over the entire process chain). The entire evaluation and execution procedure is a recommendation for the practical use in CS initiatives. Each task needs to be checked and adapted for the individual initiative. The basic structure can be adopted for specific CS concepts, such as intermediaries, open source, company internal initiatives, marketplaces for creative ideas and public initiatives etc.

A comparison of each project in the use phase was enabled in order to define the time-to-market acceleration of manufacturing technologies. Concrete values for each project were used. Five categories were related to the CIPP: 1. Context: Development Status, Problems & Risks; 2. Input: Resources; 3. Process: Structure; 4. Product: Benefits. Each assessment of the five R&D projects was reviewed separately. All criteria values per project were calculated with the mean, for each period of time. The mean is the only measure of central tendency that uses the information from every single score. The following paragraph describes the main findings in each of these categories.

The context indicates under which setting (affected problematic areas) and requirements the projects are further developed inside the firm. The development status (context) was determined via the project results, stakeholder requirements, new field of application as well as customers' and cross-functional understanding of the project. The questions on problems and risks (context) dealt with missing financial resources, lack of relevant team members, technical and quality issues, missing management support and potential risks.

The input outlines how the project was supported with necessary resources. A critical aspect was that the resources, funding, and timing (input) which should have been defined in the initiation phase, were only partially planned for the use phase. The lacking knowledge regarding which projects will succeed from previous phases and where these will be positioned in the future firm structure, was problematic. Officially planned, funded and allocated resources were analyzed in terms of available equipment as well as the involvement of the idea provider and of new team members.

The process characterizes how the project was setup in the firm and how efficient their workflows are. A further critical aspect was that the structure of development (process) was not defined either in the initiation phase, due to lack of process knowledge. The priority and work focus, project structure, efficiency of the setup, communication with interfaces and systematic search for know-how sources and development partners are the main factors in this category. An important aspect is the actual development process of the projects and how it is performed.

The product indicates how each project defines its designated benefit definition situation. The benefits (product) were analyzed in terms of cost savings, positive benefits for working conditions in the production environment, productivity, lead time reduction and, impact on the quality of the final product. The data was linked with a final MRL assessment.

The article demonstrates the individuality of each project. The objectivity with several categories and criteria maintains a clear evaluation process of the outcome. The assessment of the projects and the evaluation of the CIPP show a first glance that CS can influence on the development and implementation of manufacturing technologies in a corporate environment. The defined goals were reached for three technologies. The initiative was perceived as successful, considering the fulfilment of the objectives, the identification of aspects for improvement and the results of the evaluation.

The data implicates that the CS initiative provided the firm with external technical knowledge and resources. The simultaneous engagement of internal R&D activities and the CS initiative enabled the development of manufacturing technologies over a short period of time with a high MRL. The technologies were evaluated, adopted and partly implemented in the firm. The CS initiative pushed the manufacturing improvement and thereby accelerated the time-to-market of new products.

5.1.2 Technology evaluation score for manufacturing technologies

The constant assessment of manufacturing technologies is essential for manufacturers. Thus, the dissertation addresses the question, how firms can successfully define the value of selected manufacturing technologies at the operational TM level. Research gaps, like requirements of more industry-related models and the integration of arising criteria (environmental and social) in the manufacturing industry, are answered and a measure to compare R&D projects impacted by OI formats with non-impacted R&D projects is provided.

The corresponding technology evaluation score (TES) model was developed by using criteria of the product cycle-oriented evaluation of manufacturing technologies and the manufacturing outputs criteria depending on the product and volume linked with existing operative models in the firm. The outcome of the model is a TES. It includes seven weighted main criteria: 1. economic efficiency, 2. quality, 3. product functional capability, 4. environmental health and safety, 5. strategy, 6. resource input, and 7. social aspects. The model is used for efficient technology decisions at the operational level. The technology development and implementation are executed for those technologies, which achieve a certain limit (e.g. at least a minimum score of 50 %). Other criteria, like assigning a certain amount of R&D budget, are also possible.

The consideration of the model in daily business and frequent technology planning enables firms to quickly get an overview of the technologies in development and implementation. If the management wants to implement technologies with a strategic improvement focus, e.g. environmental, health and safety (EHS) in the plant, the partial score of EHS could be plotted and technologies with high ratings in EHS could be prioritized.

The sensitivity analysis revealed that the model generates consistent distributed scores. The utilization of the model enables the firm to overview various technology criteria. The firm can constantly align their technology exploitation based on their internal needs. The model allows an internal customization of the criteria. It helps to constantly manage the technology projects and adapt these according to the firms' needs. Furthermore, the model helps to react to market changes and governmental regulation, and thereby generates a competitive advantage for the firm. To leverage these advantages, the R&D expenses have to relate to the evaluation outputs in the firm.

5.1.3 University-industry collaboration indicators for manufacturing technologies

To obtain suitable indicators for university-industry collaboration (UIC) R&D projects at the operational TM level, it is necessary to connect UIC and TM processes and derive important indicators for this new process. The process components based on the qualitative data are integrated into the process to create a holistic framework (see Appendix 2). The UIC lifecycle based on (Perkmann et al., 2011) implies four stages and its assessment: inputs, in-process activities, outputs, and impact. The TM framework is based on the TM procedures of Gregory (1995), Rush et al. (2007), Levin & Barnard (2008), Cetindamar et al. (2009), and Schuh & Klappert (2011). The framework consists of five subsequent TM activities and two parallel activities. The input of the collaboration is pre-defined (i.e., technologies are already identified and selected by the partners, budget and resources are allocated based on the grant statement). The in-process planning is structured like a technology acquisition. While the in-process development is still part of the technology acquisition, the readiness of the technology allows to exploit it inside the firm and the university. The output is the fully utilized technology exploitation. The exploitation normally goes hand in hand with the protection (e.g. invention disclosures): due to the open innovation approach multiple stakeholders have been exploiting the technology during its development. A joint protection strategy usually starts during the acquisition and is executable at the end of the funding period.

The entire article focuses on the in-process activities (technology acquisition, exploitation, evaluation and supporting activities) and partly on the output of the university-industry collaboration R&D project. The clear spotlight on the executers of these TM phases, namely PhD students in this case study, facilitated to analyze the in-process mechanisms in depth. The MRL assessment of the UIC R&D projects provides a first hint about the progress of the evolved cases. The aims were to broaden the set of indicators for manufacturing technology UIC in R&D projects.

The variety of indicators confirms Barnes et al.'s (2002) view that the success of a collaborative project is influenced by a complex interaction of indicators. If the indicators are correctly managed, these show the positive effect on the observed success of knowledge and technology exchange. Thus, if the same indicators are mismanaged, a corresponding negative effect occurs on the observed success of knowledge and technology exchange (Ankrah & AL-Tabbaa, 2015). As Siegel et al. (2003) already stated, organizational and managerial issues are the main critical indicators for the success of university and industry relationships.

The article 3 measures existing indicators of literature in each TM phase. Due to the focus on the in-process activities (project level), most indicators measure the following process components: project planning, governance establishment, project execution, commitment, expertise & availability, technology transfer & adaptation, network & communication, and main issues. New indicators were derived out of the data for the process components:

- Project execution: Recheck responsibilities and workload allocation; Implement stakeholder management activities; Shift as many development steps as possible into the digital world – detached from production capacities
- Expertise & availability: Agility and flexibility in access to resources
- Technology transfer & adaptation: Execute technical and steering committee meeting to monitor transfer & adaptation (apply MRL reviews); Lift direct benefits by focusing on long hanging fruits of firm processes in the transfer steps; Increase direct communication with the end users; Allocated similar technical systems at both partners; Include supplementary OI approaches; Specify clear hand over after technology development (MRL6) to the end users for implementation on the shop floor

The MRL illustrates the progress of each R&D project. In one project, many students were involved via the CS initiative in article I. The project received additional management support and the MRL of this project was ahead all other projects. This implicates that the use of supplementary OI approaches can help to accelerate the development of manufacturing technology in UIC R&D projects.

In summary, the article provided detailed insights into the execution of UIC projects at the operational TM level of the firm and highlighted important indicators in each phase of this OI format.

5.1.4 Manufacturing readiness level comparison (Open innovation vs. Traditional R&D)

To strengthen the findings and conclusion of the dissertation, internal accessible project documents (review documents) were matched with internal Enterprise Resource Planning information (cost structure) of the R&D unit. The data set distinguishes between traditional R&D projects and projects, which were executed in the described UIC setting (see article 3). Figure 5-1 illustrates the R&D cost to achieve the respective MRL.

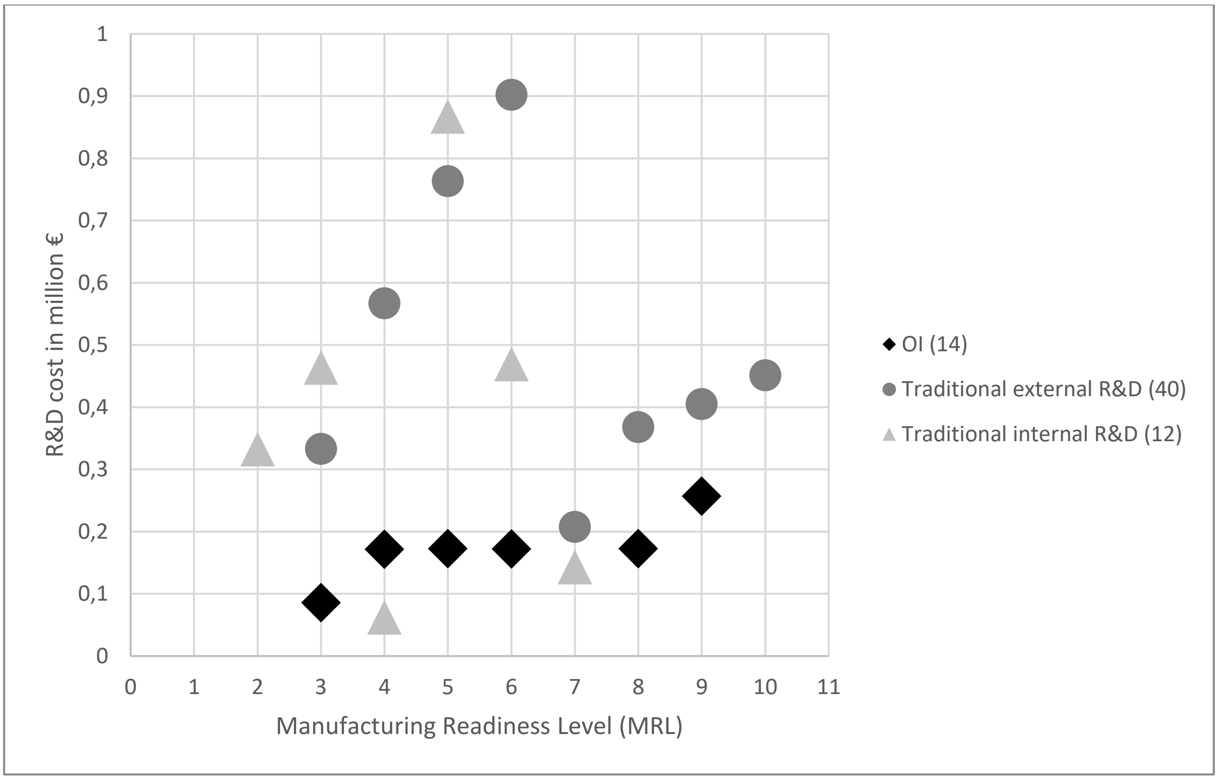

Figure 5-1: OI vs. traditional R&D: Average R&D cost per MRL (Own illustration)

For the traditional R&D projects the data set distinguishes between internal and external projects. A project is counted as external if more than 50 % of the R&D cost is allocated to an external stakeholder (i.e., supplier, customer, partner). 80 % of the analyzed projects are external projects (incl. the UIC projects of article 3). This demonstrates that this specific R&D unit in the firm is mainly assessing manufacturing technologies with the backing of external knowledge and resources. The diagram maps the average R&D cost to achieve the individual MRL per collaboration type. Thereby, science based OI projects require less R&D costs than most traditional projects. The data set supports the assumption that OI formats can reduce both R&D and implementation costs of manufacturing technologies. There is no data about the value of the individual projects as well as the development time. This missing data could significantly bias the results.

5.2 Implications

5.2.1 Theoretical implications

The results of this dissertation indicate that OI formats for manufacturing technologies do not yet have a solid foundation, as partly stated by Lichtenthaler (2008) and Rubera et al. (2016). The effective management of technology requires practical management tools to support decision-making and action, underpinned by well-founded conceptual frameworks (Phaal et al., 2006). As a main implication of this dissertation, operational TM can in fact provide a certain adaptable framework to merge it with existing attempts of other businesses and industries in OI to impact the R&D of manufacturing technologies.

The first analyzed OI format - CS - addresses a so far non-listed CS application area in literature (Kleemann et al., 2008; Whitla, 2009): the development and implementation of manufacturing technologies. As far as I know, this is the first research on a CS initiative starting from the ideation phase via prototypes in a real-manufacturing environment to the final transfer into R&D projects. The dissertation provides insights and a model on how to design and effectively validate a CS initiative in the manufacturing sector. Furthermore, it points out how to incorporate the generated ideas into firm processes (Hoornaert et al., 2017). The model addresses the need of evaluation guidelines to standardize CS and make it comparable and evaluable in the B2B or manufacturing sector (Kärkkäinen et al., 2012; Simula et al., 2015). The time-to-market aspect, which is crucial for the competitiveness of firms, is included as MRL in the model. Thereby, the model enables a final assessment how the OI format impacts the value of the created ideas. The empirical evidence proves that the involvement of an external crowd creates new ideas, resources, and internal management support. Furthermore, it illustrates that external problem solvers (in this case, students) can create initial prototypes in a CS initiative, that are worth to be pursued by internal R&D activities. Thereby, the initiative saves internal R&D resources and shortens the manufacturing technology development time (Tapscott & Williams, 2010; Terwiesch & Xu, 2008). This implicates that CS is applicable in a manufacturing perspective to develop ideas for real processes, services, or products. It supports the development, evaluation, and adoption of manufacturing technologies and thereby, accelerates their time-to-market.

The long-standing need of industry-related evaluation models for technologies at the operational level of TM to increase competitive advantages (Skilbeck & Cruickshank, 1997) is addressed by the developed TES model. The model provides a first attempt to evaluate strategically selected technologies in their application of an individual production environment with the consideration of social and environmental criteria to access the technology on the micro-economic level. The sensitivity analysis supports the applicability of the model in the industry. The model is validated with a sensitivity analysis and generates consistent data for decision-makers. It is adaptable and allows the customization of each criteria. Thus, the dissertation contributes a deductively developed valid evaluation model to research. It supports the investment justification process, decision and analysis process, and knowledge management (García A & Alvarado I, 2013) during the implementation of manufacturing technologies by a standardized and aligned model within production and management. By this means, the model adds a new tool to the technology development cluster for manufacturing technologies and supports the decision-maker at the operational level in the firm.

The second analyzed OI format – UIC – addresses the need to confirm the appropriateness of university-industry collaboration life cycle indicators described in literature. Furthermore the need consists in specifying more precisely the UIC life cycle indicators for different types of cooperation (Seppo & Lilles, 2012; Barnes et al., 2002). Analyzing UIC at the operational level of TM enabled a new research entry-point into the UIC lifecycle. Thus, the dissertation focused on the in-process activities and not as in previous studies on the inputs, outputs, and impact stages of the UIC (Perkmann et al., 2011; Seppo & Lilles, 2012; Piva & Rossi-Lamastra, 2013; Rossi & Rosli, 2015; Fernandes et al., 2017; Albats et al., 2018). The longitudinal and in-depth analysis provided interesting contribution to the UIC literature at the operational TM level and their cause-and-effect dynamics in short term and long term scales (Ankrah & AL-Tabbaa, 2015, S.402).

To the best of my knowledge, an abductive approach with a focus on the in-process activities of UICs at the R&D projects level for manufacturing technologies has not yet been published. Therefore, the findings based on a qualitative research study present a new contribution. The diverse increase of maturity readiness levels of the manufacturing technologies during the in-process activities exemplifies that newly derived important indicators of this dissertation, like supplementary OI approaches, shifting of development steps into the digital world and clear responsibility handovers, are crucial for the success of the operational TM of manufacturing technologies in UICs.

OI as a field of research needs hard empirical evidence on the interplay between OI and performance. Previous studies were mainly based on case studies relying heavily on firm level surveys (Kirschbaum, 2005; Laursen & Salter, 2006). In contrast to these studies, this dissertation provides empirical evidence at the operational R&D project level. It implicates a positive relationship between OI and (project) performance, provided that the right TM procedures are in place. The dissertation gives a detailed view on how OI activities are executed and managed within the field of manufacturing technologies in a large R&D intensive firm.

Implications from the analysis of the practices at the operational TM indicate that the momentum has arrived to advance from existing procedures in R&D activities for manufacturing technologies towards more open-minded approaches that include new methodologies such as OI.

5.2.2 Practical implications

The entire dissertation is closely linked to practical implications due to its defined organizational allocation and applied qualitative methodologies. The combination of OI formats with the operational TM level for manufacturing technologies clearly describes the boundaries of the dissertation. Due to this narrow and static focus of the dissertation, practical implications can only be provided for this specific environment.

Using external knowledge can speed up processes, reduce costs, introduce more innovative ideas and reduce time-to-market (Sloane, 2011b). More and more CEOs see collaboration as key to their success with innovation (IBM Institute for Business Value, 2021). They know they cannot achieve their innovation targets using internal resources alone (Sloane, 2011a). Especially with the upcoming technological breakthroughs which will have a significant impact on the size and shape of the world's manufacturing and high-tech sectors, firms will not be able to survive without external partners. Technology lies at the heart of any manufacturing firm. Thus, it is obvious that managers must apply advanced management procedures, like TM and OI. The following section presents implications how managers can benefit from a combination of these procedures at the operational level.

CS offers firms a variety of potential (e.g., external technical knowledge (Chesbrough, 2003), increased resource efficiency (Eisenhardt & Tabrizi, 1995) and innovation speed (Akman & Yilmaz, 2008)). The link between the CIPP model and the CS process offers practitioners a guideline to execute and measure the CS initiative in a manufacturing technology perspective. By using the model, efforts and objectives can be defined for the CS initiative. CS initiatives become evaluable and comparable among themselves. CS supports the manager to accelerate the time-to-market of new products by accelerating the development and implementation of manufacturing technologies. Therefore, the CS initiative needs to be well designed and incorporate the real-manufacturing environment as well as knowledge of the firm. Especially, transparent benefits (cost savings), a well-defined structure (involvement of idea providers), defined problems & risks (financial resources) and a constant development status (clear application and stakeholder requirements) are key elements in CS initiative to accelerate the time-to-market of manufacturing technologies. For manufacturers, CS will receive growing importance to leverage cost reduction and process efficiency.

The rise of new technologies creates new competitive advantages and increases productivity across sectors and geographies (PWC, 2016). Thus, it is crucial for each firm to evaluate these technologies on different levels of the firm to assess their impact on firm's competitiveness. Consequently, the knowledge about the value of manufacturing technologies is crucial to setup the R&D strategy at each level of the firm. The developed TES model enables practitioners to internally prioritize and budgeted selected manufacturing technologies at the operational level. The standardized procedure ensures a common understanding of each impacting factor in the manufacturing environment and improves the cooperation between management, project managers and the shop floor. Business factors including the direct impact on the product cost as well as non-direct monetary factors (e.g., workplace safety) enhance the importance of some technologies that might not be considered relevant when only looking at one set of factors. Thus, the model supports the decision-making process based on a holistic quantitative view at the operational TM level.

In recent decades, governments have dedicated increasing resources to supporting research collaborations between firms and universities, based on the assumption that technology transfer will occur. Firms' motivations to execute this kind of collaboration are broad, ranging from sources of new knowledge and technologies, stimulation of creativity, decrease of R&D investment, access to international cooperation networks and reduction of R&D costs etc. (Caloghirou et al., 2001; Cassiman & Veugelers, 2006; Santoro & Chakrabarti, 2002; Tether, 2002; Bayona Sáez et al., 2002; Schartinger et al., 2001). To fully benefit from interactions with universities, firms should include UIC into their TM processes in an elaborated framework at the operational level. In the manufacturing sector, practitioners can not only depend on project management procedures and need to expand the stage-gate processes with MRL reviews. The practitioners might fail to keep the progress and to justify the efforts and expenses of the activity inside the firm without including indicators like adequate resources, teamwork, training, roles, re-baselining, applied research, access to leading edge technology and clear hand overs etc.. The dissertation provides practitioners with know-how to setup UIC R&D projects for manufacturing technologies at the operational level.

Practitioners can use the provided guidelines, indicators, and models of this dissertation for execution, evaluation, and decision-making purposes. Thereby, in-house R&D and OI should be viewed by management as complements.

Finally, it is important for (top) management to encourage and supervise OI for manufacturing technologies at the operational TM level as only they set the overall innovation strategy of the firm. They must understand that the age of "open technology management" has already begun and that OI formats enable firms to accelerate their R&D activities of manufacturing technologies. Open technology management means that TM evolves into an open collaborative context in which external and internal sources (i.e. technologies, know-how, individuals, organizations) are combined and operated in generally open but specified systems to jointly push technological innovation. Thereby, TM is the framework to leverage the underlying potential due to the interconnectivity and diversity of all sources at and between every organizational level.

5.3 Critical reflection

Although the results of the dissertation provide several contributions to the application of OI formats at the operational TM level in the manufacturing perspective, respective evaluation guidelines and their impact on time-to-market, the present dissertation has certain limitations that should be considered when interpreting the results. These limitations provide a starting point for future research.

First, it was impossible to summarize all the discussed views, perspectives, and approaches into a single holistic picture. The reviewed literature on TM, operation management and OI is not fully comprehensive because the field is far more complex and has a much larger body of literature than what can be feasibly addressed in a single dissertation project. Other theories and interactions may also be important for the operational management of technologies. The derived research procedure (Figure 1-2) is a first attempt on a micro level, to connect OI with the operational TM. All articles represent stand-alone studies but are closely linked in their underlying story line. While the development of insights was on similar levels, each article had a different focus. Furthermore, an evolution of concepts can be observed in the articles because they were completed over an approximately four-year research period.

The used alternative methodological approach in article 3 (i.e. abduction) must meet the expectations of both, research and, increasingly, practitioners in order to convince them (Sandberg & Tsoukas, 2011). The goal of abduction is to match theory and reality for solving a practical problem by systematically combining empirical data and insights from theory (Storbacka, 2011). The article briefly describes the reasons for selecting an abductive reasoning approach for the empirical research, but the choice for the research method (traditional case study) was made primarily due to the authors' main data acquisition method in the firm. There are other suitable methods and concepts available such as action case study. Thus, it can be argued that the dissertation is as mixture of a traditional and action case study research. The main difference of action case study compared to traditional case-study research is the position and role of researchers as participants in a group who accompany the process but do not take a central stage. Action case study allows real-time testing of theory in a natural environment (Pettigrew, 1990), provides both concrete results and conceptual results in terms of proposed changes to the theoretical framework (Braa & Vidgen, 1999), allows gathering more profound and crucial information (Ottosson & Björk, 2004), leads to research projects with temporary interaction (Pettigrew, 1990), active participation in practical projects without taking center stage or making decisions, and provides managers with new insights to solve practical problems (Braa & Vidgen, 1999). All these points fit to the research setup of this dissertation. Each of the analyzed OI formats as well as the technology evaluation model is based on a one case scenario, in which the researcher was part of the analyzed R&D unit with access to profound and crucial information and provision of closed-loop feedback to the managers. In retrospective, the research methodology could have been chosen more carefully, especially for the first and third sub-question. This lack of rigor could result in non-agreement within research on the findings due to a lack of full acceptance of the results.

For the qualitative study case study (article 3) that comprises one main empirical part of the dissertation, the sample size is quite small, with a total of 20 interviews and a focus at the operational project managers. In this study, only context-specific indicators were derived and not common indicators Therefore, the findings cannot be easily generalized or transferred to other large manufacturers or industries. Furthermore, the dissertation was compiled in a R&D unit of a German manufacturer, and the results could differ in another cultural or industrial setting.

This similarly applies to article 1, which insights are limited to a single in-depth exploratory study design. Thus, the gained insights to develop and use the evaluation model and analyze their usability are limited to such case. The time-to-market acceleration for manufacturing technologies was analyzed without defined time values as baseline. There is no comparison with similar R&D methods like UIC, internal R&D, etc.. More specifically, the findings are not quantifiable in comparison to procedures with the same focus, number of resources, timeframe, setup, and support. The identical limitations concern the presented CS evaluation model and technology evaluation model, which is based on a one case scenario. The sensitivity of developed criteria was not discussed across different industries and technologies.

The implication that CS accelerates time-to-market of manufacturing technologies is based on a set of criteria and MRL assessments. This set may be incomplete. Additionally, a common understanding of the criteria was not established inside the evaluation network (development status, resources, benefits etc.).

The research observed OI formats at the operational TM level two times without providing concrete answers about the sequences or the completeness of presented models and indicators (i.e., guidelines for managing OI at the operational TM level).

Despite these limitations, I believe that the dissertation provides an empirical verification that was previously lacking in the literature on OI formats at the operational TM level of manufacturing technologies.

5.4 Outlook and future research pathways

The rise of new technologies and changes driven by global trends, climate change and pandemics will not decline in the future. In contrast, it will dramatically increase, and manufacturers will face more pressure to find appropriate ways to quickly respond to such changes. There will be much more of everything - more technological innovation in more locations from more individuals focusing on details and customization. Manufacturing technologies will become cyber-physical systems with escalating complexity and connectivity. The manufacturing industry will be reinvented and finding the appropriate answers regarding the management of technology and innovation will become more essential than ever. Interdisciplinarity, flourishing manufacturing innovation ecosystems with access to external knowledge and resources will be crucial determinants for the survival of manufacturers.

The cyber-physical production systems, which are systems of collaborating computational manufacturing objects in intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet (Monostori et al., 2016), in combination with disruptive technologies in areas such as artificial intelligence, additive manufacturing, robotics, sensors, and virtual reality are accelerating the pace of innovation in manufacturing. Technologies are becoming more powerful, reshaping user experiences, operations, and, in the end, the productivity and efficiency in the manufacturing industry. New business models will arise due to data value creation, new cost models, and services. The impact of these technological innovations is amazing, but it is just a preview of what is coming. According to Moore's law, technology will be about ten times as powerful in five years as it is today. Considering technologies, like artificial intelligence, quantum computing or neuromorphic hardware, technology may be a thousandfold more powerful in 10 years. This future technological perspective indicates that keeping pace with innovative technology will be even more difficult in the future.

Accordingly, one of the essential technological as well as managerial capabilities in upcoming years will be building and utilizing all kind of innovation ecosystems. Research findings show that the industry 4.0 technologies will have a significant positive impact on a firm's OI (Mubarak & Petraite, 2020). Specific infrastructure (e.g., 5G and cloud computing) will provide easier access for externals to firm's manufacturing data. External partners can be plugged into secured environments in a fast way and the collaboration can be enlarged on different levels. Data will become a strategic and operational enabler. Thus, there is no doubt that these innovation and technology developments affect the R&D and operations of firms in a dramatic manner. Technology will enable firms to speed up their innovation funnel with the power of academia, small businesses, and start-ups. Even in 1969, Allen & Cohen argued that "no research and development laboratory can be completely self-sustaining. To keep abreast of scientific and technological developments, every laboratory must necessarily import information from outside" (1969, p. 12) However, the majority of the manufacturing industry still doubts the urgency of such external collaborations.

Within the described developments, there are several opportunities for manufacturers. The manufacturing processes can be created, designed, and evaluated with the help of the "crowd". This can help decrease the risk of failure for innovation and increase the scalability of a new manufacturing technology. The time-to-market can be accelerated by rapid prototyping and testing ideas quickly with a broader audience (incl. end users). The success or failure of a technological innovation can be measured more directly and accurately with digital simulations of each product lifecycle stage (design to manufacturing up to maintenance).

Promising future research pathways can be categorized into strategic and operational levels.

At the strategic level, an interesting field of study is seeking to understand the mechanisms, connectivity, and interdependency between OI and operational management in more detail.

This is increasingly interesting because the pace, intensity, and manner of operational approaches is changing dramatically. For example, real time data capturing and analyzing may become a requirement for doing business, rather than a competitive advantage (PWC, 2016). Another promising research path at the strategic level is driven by innovation ecosystems. New forms of innovation ecosystems are emerging that are not yet understood (or even defined) in detail. Here it seems that even large high-tech firms must participate in an existing ecosystem or create their own to stay innovative and competitive.

At the operational level, there are various interesting pathways for future studies. First, there is a need for a better understanding of the multi-level landscape of OI and the interdependencies with TM. OI is relevant and has implications for how innovation activities take place at the individual, organizational, inter-organizational and even higher levels of analysis, such as regions or industries (West & Bogers, 2014, 2017; Bogers et al., 2019). A multi-level perspective is crucial for advancing theoretical models as it allows breaking these models into multiple components and then tracing links among them at different levels of analysis (Salvato & Rerup, 2011). For instance, understanding factors at different levels of analysis seems particularly important, as elements at the operational level of analysis (e.g. derived structures and processes at the operational level of this dissertation) may result in contingencies at higher levels of analysis (e.g. various stakeholders in an innovation ecosystem setting). Second, it would be worth investigating in more detail the in-process activities in OI formats for manufacturing technologies. The dissertation provides first insights how managers can leverage OI for their manufacturing technology R&D projects and how to manage R&D projects in the context of OI. However, the identification of team characteristics that are beneficial for open or closed innovation projects as well as when partners should be involved in the project and for how long (Du et al., 2014), are further relevant criteria, which would support the efficiency of OI approaches in R&D projects. Additionally, as described in the introduction the classical new product development management approach, which has been developed for closed innovation projects, might not be useful for “open technology management” projects. OI partnerships with science-based and market-based partners tend to be managed in different ways (Du et al., 2014). Additional and deeper integration with theories and theoretical questions that are well-established in management research (e.g. dynamic capabilities theory of Teece et al. (1997)) should address this issue to come up with entirely new management approaches. Applying termed models and frameworks of this dissertation in deductive approaches can provide a basis for further research. Further empirical studies to validate or extend the findings of the dissertation through quantitative studies, the transfer of the models on other OI formats to standardize the methodologies and validate them, the investigation of the findings under other cultural or industrial settings, and the adoption to multiple case study design in other manufacturing context (cross-case analysis) might help to develop a more robust picture of the findings and to create holistic frameworks and intersection of these two management theories.

The last highly promising research pathway reveals itself by linking disruptive technologies with OI and TM procedures. There is a need to interlink these two aspects on each level of the firm considering the described impact of technology at the operational level of a firm. For example, additive manufacturing provides firms the possibility to realize their ideas with a minimum of time and resources than what was required a decade ago. This technology is already incorporated in different management approaches (e.g. as part of the prototyping toolbox in design thinking). Research already showed that cyber-physical systems in combination with logistic models can improve planning, controlling and monitoring a production (Seitz & Nyhuis, 2015). If these systems share information and automatically interact with each other, soon everyone could have access everywhere to everything on the Internet. The combination of information technology, operational technology and new technologies as artificial intelligence, cloud computing etc. will dramatically define practice as well as strategy, innovation, and operation research. It will enable to connect the dots between these research fields in a predictive, connected way (e.g. via data analytics). This creates a clear need of bold management approaches to leverage these insights and connections based on enabling technologies inside flourishing resilient innovation ecosystems. The digital future of firms will be defined by technology and management.

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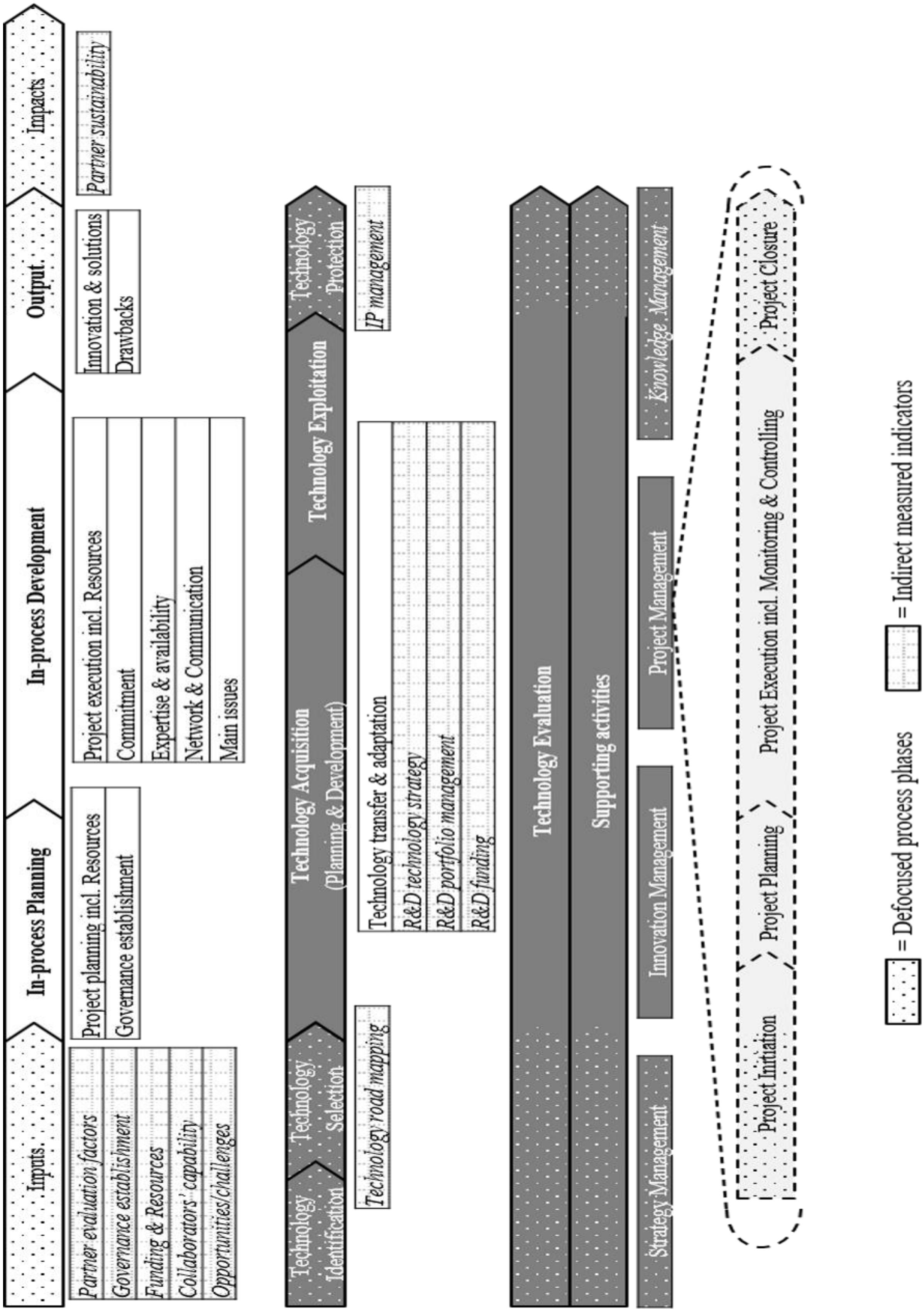
Appendix

Appendix 1: Manufacturing Readiness Level Definition (Own illustration)

MRL Definition	
Conceptualization	**MRL 1:** Basic manufacturing implications identified
	MRL 2: Manufacturing concepts identified
	MRL 3: Manufacturing proof of concept developed
Manufacturability	**MRL 4:** Capability to produce the technology in a laboratory environment
	MRL 5: Capability to produce prototype components in a production relevant environment
	MRL 6: Capability to produce a prototype system or subsystem in a production relevant environment
Industrialization	**MRL 7:** Capability to produce systems, subsystems, or components in a production representative environment
	MRL 8: Pilot line capability demonstrated; Ready to begin low rate initial production
Serialization	**MRL 9:** Low rate production demonstrated; Capability in place to begin full rate Production
	MRL 10: Full rate production demonstrated and lean production practices in place

Appendix 2: Elaborated framework with measured process components (Own illustration)



Appendix 3: Quotes - Interviewees

Project execution - Recheck responsibilities and workload allocation

“The workload should focus more on the development than the management tasks. In the beginning there have been too much management tasks like unclarified reporting structures, sense and purpose of the development.” (Project lead B)

Project execution - Implement stakeholder management activities

“My direct customers are all or most of them in city A. Whenever I am there, I speak to them and otherwise by phone and email. However, I would have to be in more contact with them.” (Project lead A)

“At the moment we are in debates, because we are not allowed to do anything, where the works council does not agree.” (Project lead B)

“I’m directly working with the persons and department, which will be the end user of the technology, procure a machine and profit from it.” (Project lead C)

Project execution - Shift as many development steps as possible into the digital world – detached from production capacities

“We do not need to push ourselves into the production slots like other colleagues as a R&D department. We are a bit detached from it. And that is what I think is essential, which speeds things up.” (Project lead A)

“If I want to get a cutting parameter for a component, then I don't have to deliver the component to city B and machine it. It’s enough to cut a material sample to validate the digital developed procedure.” (Project lead C)

Expertise & Availability - Agility and flexibility in access to resources

“At the beginning the collaboration was a little bit stuffy. We had to stick clearly to the agreed machine hours. After this planned hour, the testing day was over. It was very inflexible, so that you needed an accurate planning. […] I hope that it will be possible to get access on short notice onto the machine in the future without using the official way.” (Project lead C)

“I’m mainly depending on the colleagues. Every machine is specialized. To use them, I completely depend on them.” (Project lead C)

Technology transfer & adaptation - Lift direct benefits by focusing on long hanging fruits of firm processes in the transfer steps

“It makes sense to discuss directly with the people, if there are any other issues beside the problem statement in mind, which could be fixed in a quick and easy way. This really makes the people happy.” (Project lead C)

Technology transfer & adaptation - Increase direct communication with the end users

“I think that people in the same room, almost face to face, are much better off than E-Mail traffic or telephone contact, because that usually results in misunderstandings and frequent back-and-forth shifts. Furthermore, I do not think that the worker on the shop floor like performing virtual meetings. I cannot imagine that. For the communication ways I find it important to be on site. I would not say too little. I think every 2-3 months is a good turn.” (Project lead C)

“It is simply not possible to implement a technology that I developed in city B in any manufacturing department in city A in such a way that it really gets there […]. You cannot change the people there, from here. That must come from them. If they want to and say "yes, please, please help us", it can work but usually it fails because of the real implementation / application / use when people have to change their behaviour.” (Project lead D)

Technology transfer & adaptation - Allocated similar technical systems at both partners

“Of course, it would be ideal if the same system was installed in city A as in city B, so that 8 weeks could be programmed in city B and the process transferred to city A in one week.” (Project lead D)

Technology transfer & adaptation - Specify clear hand over after technology development (MRL6) to the end users for implementation on the shop floor

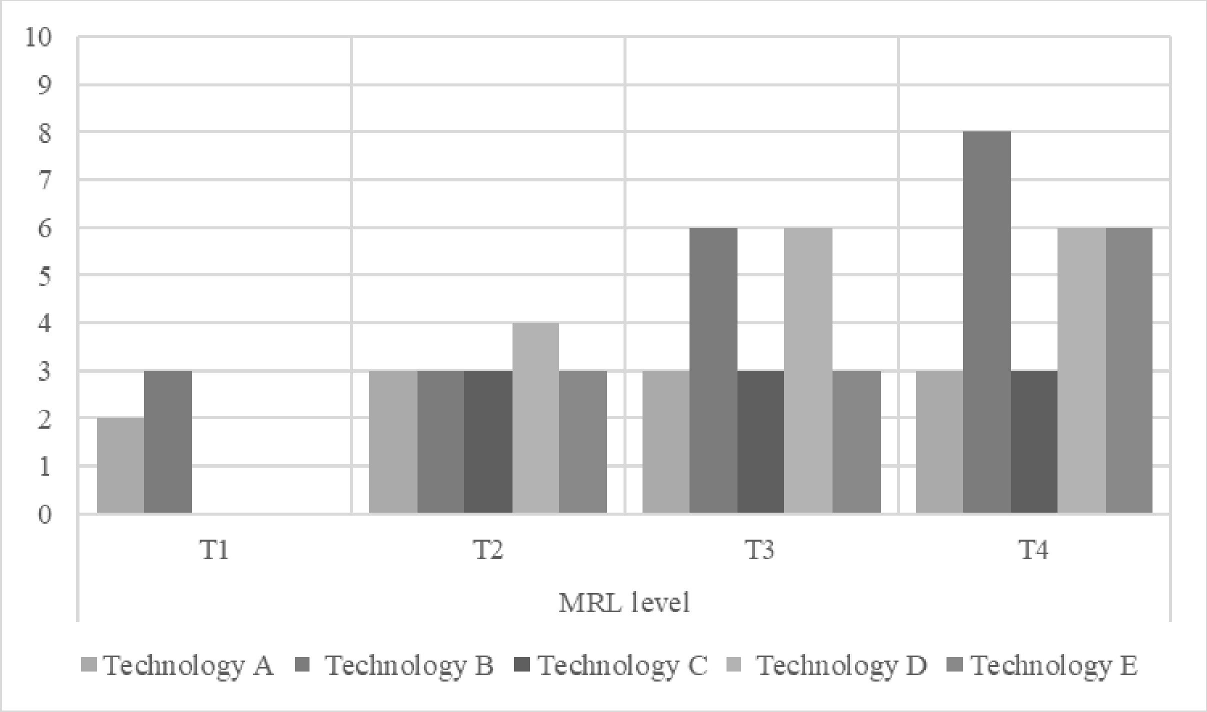
“It should really go into production now. The hand over to manufacturing started and the machine is ordered.” (Project lead D)

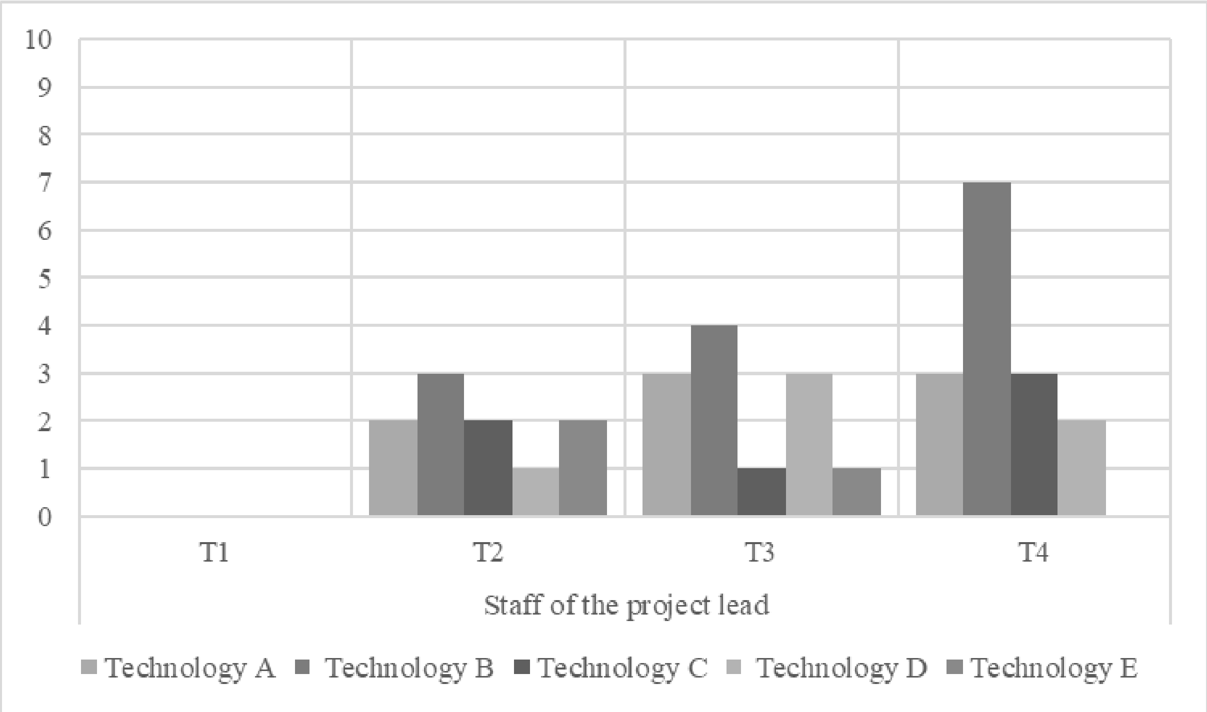
Technology transfer & adaptation - Include supplementary open innovation approaches

"The challenge made the project more attractive. It pushed in that sense. It has not advanced technology now, but it has been pushing stakeholder attention […]. That was very well received." (Project lead B)

"Challenge will help me on the one hand to connect with new experts inside our firm. On the other hand, I might find students who have ideas in this area and are enthusiastic about the topic. It would certainly be a very good pre-selection." (Project lead B)

Appendix 4: MRL levels over time of UIC R&D technologies and included staff from the project lead





Pages 133-134 contain private information and have thus been removed from this document.

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Appendix 6: Content structure of the attached data medium

00 Dissertation

10 Article Dataset

- Article 1: Data - Project survey Evaluation
- Article 1: Data - CIPP and CS
- Article 2: Data - Example model
- Article 2: Data - Sensitivity Analysis
- Article 3: Interviews
- Article 3: Research process, framework, examples
- Article 3: Reports – Summary with Codlings
- Article 3: MAXQDA18 File

20 Published Articles

30 Curriculum Vitae Articles

Statutory Declaration

Eidesstattliche Erklärung

und Einverständniserklärung
nach § 6 Abs. 2 Nr. 5, 6 und 7 der Promotionsordnung der Wirtschafts- und Sozialwissenschaftlichen Fakultät der Universität Potsdam vom 10.07.2013

Von:

Name: Dreßen

Vorname(n): Sebastian Till

geb. am:

in:

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DECLARATION OF CO-AUTHORSHIP

This declaration concerns the following article/manuscript:

1. The declaration applies to the following article							
Title of article	**CROWDSOURCING FOR MANUFACTURING TECHNOLOGIES – ACCELERATION OF TIME-TO-MARKET**						
Article status							
Published	☒	Accepted	☐	Submitted	☐	In preparation	☐
Full reference in case of publication:	Dreßen, S., Hoelzle, K., Neuenhahn, T. & Weinreich, I. (2018). **Crowdsourcing for manufacturing technologies - Acceleration of time-to-market**. In 25th Innovation and Product Development Management Conference (IPDMC). Porto, Portugal.						

2. The PhD student's contribution to the article (***please use the scale A-F as benchmark)*** Benchmark scale of the PhD-student's contribution to the article **A.** Has essentially done all the work (> 90 %) **B.** Has done most of the work (60-90 %) **C.** Has contributed considerably (30-60 %) **D.** Has contributed (10-30 %) **E.** No or little contribution (<10 %) **F.** Not relevant	**A, B, C, D, E, F**
1. Formulation/identification of the scientific problem	A
2. Development of the key methods	A
3. Planning of the experiments and methodology design and development	B
4. Conducting the experimental work/data collection/obtaining access to data	B
5. Conducting the analysis of data	A
6. Interpretation of the results	A
7. Writing of the first draft of the manuscript	A
8. Finalisation of the manuscript and submission	B

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3.	See following pages	Iris Weinreich		See following pages

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Place, date: München, 02.05.2021	Sebastian Dreßen

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