Tampere University

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Manufacturing Firms' Processes and Practices for Creating Radical Manufacturing Technology Innovations

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ACADEMIC DISSERTATION
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Lift yourself up by your Self.

- Bhagavad Gita, Chapter 6, Verse 5.

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The wisdom of staying away from reinventing the wheel is quite prominent in mainstream managerial practices for developing new production processes, which rely on procurement of proven industrial manufacturing technology solutions. As a fresh production process planning engineer, I wondered, where is the space for creativity and radical innovation in concepting and planning the needed manufacturing technologies, and what kinds of processes and practices are involved? I didn't know then that some years later, I would have the opportunity to find some answers to my curiosity. I am most grateful for the opportunity I have had to investigate processes and practices of managers in manufacturing firms for creating radical manufacturing technology innovations, in the form of this doctoral research work. I wish to express my sincere thanks to all the experts, peers and family who enabled this work.

I wish to take this opportunity to express my heartfelt thanks to Professor Johan Frishammar from Luleå University of Technology, for agreeing to act as the opponent for this thesis. His work is at the frontier of research on radical process innovation, particularly the less understood front end of radical process innovation. I could not have made way through my own research and publications without the support coming from your recent work in this field. Thank you for taking the time to read through this dissertation, which in itself is a great honour, acknowledgement and a very nice conclusion to this research.

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I wish to express sincere thanks to Jenny and Antti Wihuri Foundation and Liikesivistysrahasto (Finnish Foundation for Economic Education) for funding the final writing phase of the doctoral dissertation. I would not have been able to concentrate fully in this crucial time without generous support from these two foundations. Also, I wish to thank TUT graduate school's scholarship programme for doctoral researchers for financing the second phase of the data collection and research. This funding enabled me to carry out the case study research. I also wish to warmly acknowledge the Business Finland funded research project ROaMING and its leader Professor Jussi Heikkilä for supporting me at the start of the doctoral research work. I am grateful for the international research environment, peers, and the support and encouragement I received from this project and from Professor Heikkilä at a time when I was still finding my ground, research topic and research data, as a fresh doctoral candidate.

I wish to express special thanks to the anonymous reviewers of the journal articles, whose detailed review and insightful direction for finalising the articles were very helpful. I wish to express special thanks to all the managers who participated in this study. Their voluntary support and wholehearted participation in this study was crucial for realising this research. I sincerely hope that the outcomes from this study offer you new insights from your experiences and those of other managers in similar situations.

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Professor Martinsuo's research group CROPS (Center for Research on Project and Service Business) is a warm and welcoming community of passionate researchers. Besides the many intellectual discussions, writing workshops and the fun and games events, there was always help and friends available in CROPS when I needed. It's been my home base at the university and my CROPS teammates have been by my side through this entire journey.

The PhD research work was not less than an adventure; it had its challenges and unknowns to resolve, and I was often stretching beyond my comfort zone, previous skills and knowledge. Thanks to my peers from the start of my doctoral studies, Beheshte, Karan, and Toni, I had wonderful, inspiring, sincere friends with me all the way. Thanks for always being there for me! I treasure the memories of fun and delightful chats with you, sharing joys, frustrations and questions, and am glad for our friendship. I also wish to remember peers and friendships from EurOMA conferences, EDEN and ISPIM communities, which broadened my perspective of scientific management research and add to my fun memories of doing PhD research.

My Phd research involved working from distance. Unable to always work at the vibrant university campus, my neighbourhood provided me with an inspiring and supportive setting to keep me going through this long PhD research period. The neighbourhood community and friendships have been a constant source of joy, support and inspiration in day-to-day life, work being a part of it. Special thanks to Eija for the weekend walks and sincere friendship at a time I needed it most. I am grateful to Terja Koskenoja and her team from Woodio Oy for welcoming me to their pilot factory and providing me with an inspiring setting at the time of writing the thesis.

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I wish to thank a very special person, my late mother-in-law, aai. You were so alive, so active – I have heard every story from Sarang's childhood many times over! You keenly supported me and always messaged me best wishes before every presentation. You had deep love and high dreams for all of us your children, and we will always receive guidance and enduring support from our beloved ajji (grandmother).

I wish to take this opportunity to express my joy and gratitude to my two daughters Nishka and Aarika. You are kind and sweet children, and I am the lucky mummy. You are full of spark and life and there is no lack of plans and ideas for fun, evenings, outings and entertainment. Your genuineness grounds me to real life, keeping clear sight of what matters, and gives me the courage to think clear and be original – just like you.

Finally, dear Sarang, during this PhD project at times when things were tough, I always had you. You were present, standing by my side, when I made the many submissions through the process. You are a great listener and have endured my blabbering without any moans! 14 years into our marriage, and we feel that we are just getting started. This project was another one in the series of adventures we have taken up in our life. I have seen us grow, understand us and life better through these, and can't wait to start a next new one!

Pooja Chaoji
June 2023
Kirkkonummi, Finland

ABSTRACT

The study reported in this dissertation examined situations in which manufacturing firms introduce radically different and novel technologies into their core production processes. In shifting to a new and different production technology, a manufacturing firm radically innovates its core production process, which is referred to in this thesis as radical manufacturing technology innovation (RMTI). Manufacturing technologies are often complex, and manufacturing firms are unable to develop and manufacture the needed technologies and equipment themselves. Thus, to create RMTIs, they need to collaborate with equipment supplier firms. These innovation projects therefore involve concept development and implementation projects for both production process innovation by the manufacturing firm and linked equipment (product) innovation by the equipment supplier firm. Process and equipment (product) innovations are interlinked, and both need to be realised as part of the manufacturing firm's RMTI project.

The newness of a technology to manufacturing firms and the distributed knowledge among different experts from manufacturing and equipment supplier firms create knowledge gaps and pose related difficulties to the management of RMTI projects. These projects typically suffer inefficiency, rework, delays and losses, and there is a need for deeper knowledge on processes and practices for their management.

This dissertation concentrates on three major gaps in the previous knowledge on the creation of RMTIs from the perspective of manufacturing firms. First, the overall RMTI creation process, covering both product and process innovations linked with RMTI, has not been sufficiently covered in empirical research. RMTIs have predominantly been investigated as technology adoption tasks from the perspective of manufacturing firms, and how they introduce the interlinked process and equipment (product) innovations remains unclear from previous research. Second, related to this, research on high-novelty RMTIs, which also involve newness to others besides the manufacturing firm, is scarce, and the creation processes for RMTIs with different levels of novelty remain unclear in the literature. Third, the

emergence of RMTI ideas in manufacturing firms and managers' practices for searching for the needed ideas in the innovation front end remain underinvestigated and unclear in the existing literature.

This article-based dissertation comprises four original articles, two of which have been published in peer-reviewed scientific journals and two in peer-reviewed conference proceedings. The empirical investigation was carried out in two parts. First, a qualitative exploratory study on the RMTI creation process was conducted using empirical data on a wide breadth of RMTI examples with different levels of novelty. The study mapped different types of RMTI creation processes and the tasks involved in them from the perspective of manufacturing firms. Second, a multiple-case study was conducted, covering three nested cases of RMTI projects in each of the three case firms. The study investigated managers' information search practices for generating RMTI ideas at the front end of innovation.

This dissertation contributes knowledge on managing RMTIs from the perspective of manufacturing firms beyond new technology adoption and implementation. RMTIs are understood as involving wider tasks from the perspective of manufacturing firms, as radical innovation projects in such firms' core production technologies. Three types of creation processes are revealed for RMTIs with different levels of novelty. The novelty levels for RMTIs are distinguished based on whether the technology is new only to the manufacturing firm or is also new to the equipment supplier firm or to the industry and the world. Technological newness for equipment supplier firms is understood as an important part of managing RMTI projects in addition to technological newness for manufacturing firms. Four-dimensional construct of technological newness for equipment suppliers as part of RMTI projects and the corresponding uncertainties introduced in manufacturing firms' creation processes are revealed. The observed proactive search practices of top and middle managers in manufacturing firms for putting together the information required to arrive at breakthrough insights needed for creating RMTI ideas at the front end of the innovation are presented. This dissertation contributes to the practice of managing RMTIs by offering frameworks for processes and practices for their initiation and implementation covering the comprehensive tasks involved in RMTI creation from the perspective of manufacturing firms.

CONTENTS

ORIGINAL PUBLICATIONS

Article I	Chaoji, P. & Martinsuo, M. (2016). Successful creation of radical manufacturing technology innovations. In Koskinen, K., Kortelainen, H., Aaltonen, J., Uusitalo, T., Komonen, K., Mathew, J., & Laitinen, J. (Eds.), *Proceedings of the 10th World Congress on Engineering Asset Management* (WCEAM 2015), pp. 121–132. Springer International.
Article II	Chaoji, P. & Martinsuo, M. (2019). Creation processes for radical manufacturing technology innovations. *Journal of Manufacturing Technology Management,* Vol. 30, No. 7, pp. 1005–1033.
Article III	Chaoji, P. & Martinsuo, M. (2022). Suppliers' technological newness: Source of uncertainty in manufacturing technology innovations. In *Proceedings of the XXXIII International Society for Professional Innovation Management (ISPIM) Conference*, "Innovating in a Digital World," 5–8 June 2022, Copenhagen, Denmark. LUT Scientific and Expertise Publications.
Article IV	Chaoji, P. & Martinsuo, M. (2022). Managers' search practices at the front end of radical manufacturing technology innovations. *Creativity and Innovation Management,* Vol. 31, No. 4, pp. 636–650.

AUTHOR'S CONTRIBUTION TO CO-AUTHORED PUBLICATIONS

For Article I, I mapped the previous studies on RMTIs and identified the key themes and focus areas in them. Based on the findings from the analyses of previous studies, my co-author and I defined the topic of the article and discussed its prospective content. I prepared the first draft of the article, after which my co-author and I collaboratively finalised the article's content, particularly that of the Discussion and Conclusion sections. I presented the paper at the WCEAM Conference (World Congress on Engineering Asset Management Conference, 28–30 September 2015, Tampere, Finland), after which the paper was published as part of the conference proceedings.

For Article II, I selected the topic for the article and developed the original idea. I searched and identified sources of data on RMTI examples, contacted managers to seek access to the needed data, collected data and analysed them to arrive at findings regarding RMTI types, differences in creation processes and the participation of manufacturing firms and equipment suppliers across the projects. I presented an early version of the paper at the EurOMA Conference (23rd European Operations Management Association Conference, 17–22 June 2016, Trondheim, Norway) and then further developed it in collaboration with my co-author. Under her guidance, I further analysed the data to identify three types of RMTI creation processes and the participation patterns of the manufacturing and equipment supplier firms in different phases of the creation process. We finalised the first draft of the article jointly, particularly the Discussion and Conclusion sections. Feedback from anonymous reviewers guided the further development of the article. At the time of the review process, my co-author was the corresponding author and took the lead in finalising the revisions. All the revisions and changes made were considered jointly and taken into account in finalising the article.

For Article III, I developed the original idea based on insights obtained from the exploratory study. My co-author and I discussed the topic and planned the article jointly. I collected the data, analysed them and arrived at key themes and categories that inform the findings of the study reported in the article. I wrote the first draft of the article, including the results of the literature search and review. My co-author and I jointly finalised the article. We considered the feedback from anonymous reviewers and included it in the finalisation of the paper. I presented the paper at the ISPIM Conference (XXXIII International Society for Professional Innovation Management Conference, 5–8 June 2022, Copenhagen, Denmark), after which the paper was published as part of the conference proceedings.

For Article IV, my co-author and I developed the original idea and position of the paper collaboratively. I invited companies to participate in the study, collected data from them, analysed the data to identify key codes and categories and mapped patterns in managers' practices at the front end of RMTI. My co-author searched for and identified previous studies to further guide the data analysis. Under her guidance, I drafted the first draft of the article. We finalised the article collaboratively, particularly the Discussion and Conclusion sections. We considered the feedback from anonymous reviewers jointly, and we worked collaboratively to refine the article's content regarding the literature review, results discussion and contributions of the study. I searched for additional literature, and my co-author was especially involved in developing the propositions when we drafted the final version of the paper.

1 INTRODUCTION

1.1 Radical Manufacturing Technology Innovations: Background

Industrial manufacturing technologies and equipment are fundamental to manufacturing-based businesses. They guide and limit the manufacturing capabilities and capacities of manufacturing firms. New product generations, new industrial regulations and new customer and stakeholder requirements can make it necessary for manufacturing firms to radically renew or change their production technologies (Ellingsen & Aasland, 2019; Simms et al., 2021). For industries with rapid technology cycles, manufacturing firms must regularly introduce new technologies for the production of next-generation products (Appleyard, 2003). The tools and technologies used in core production processes are potential avenues for radical innovations in the production process, which can have an impact on firms' customers and market offerings. This dissertation uses the term 'radical manufacturing technology innovations (RMTIs)' to refer to processes that manufacturing firms use to introduce new technologies into their core production systems.

RMTIs involve new-to-manufacturing firm technologies, whereas high-novelty RMTIs may also be new to the industry and the world (Reichstein & Salter, 2006). An example of an RMTI is the Pilkington float glass manufacturing technology, a radically new method of production involving new equipment and technology (Uusitalo & Mikkola, 2010). Other examples of RMTIs in previous studies include the flow moulding, computerised pattern-generating and numerically controlled stitching technologies in footwear manufacture (Dewar & Dutton, 1986); novel special-purpose equipment technologies in processed food manufacture (Simms et al., 2021); and various forms of advanced manufacturing technologies, such as robotics, computerised numerically controlled machines (CNCs) (Baldwin & Lin, 2002; Bourke & Roper, 2016) and three-dimensional (3D) printing (Martinsuo & Luomaranta, 2018). This dissertation takes the perspective of manufacturing firms and considers radicalness from the point of view of manufacturing firms. The study covers the broad range of technologies with different overall levels of novelty, from those which present novelty mainly for the introducing manufacturing firm, to those technologies which are novel also for the industry and the world.

When manufacturing firms introduce new technologies, they often procure the needed technology equipment from equipment supplier firms (Lager & Frishammar, 2010; Stock & Tatikonda, 2004). High-novelty RMTIs require the development of the needed equipment as the needed technology solutions are not ready and available from equipment suppliers. This is achieved through joint development projects with equipment supplier firms (Rönnberg-Sjödin et al., 2016). In some cases, manufacturing firms may also develop the needed equipment (see examples in Milewski et al., 2015; Uusitalo & Mikkola, 2010). However, this is rare due to the specialised knowledge needed to develop new technological equipment (Lager & Frishammar, 2010; Rönnberg-Sjödin et al., 2016). Thus, equipment supplier firms are important partners in RMTI projects and bring in the linked equipment (product) innovation needed for the realisation of RMTIs.

RMTIs are a type of technological process innovation that is a distinctive organisational phenomenon characterised by a firm-internal locus and underlying components, such as mutual adaptation of new technology and existing organisation, technological change, organisational change and systemic impact (Milewski et al., 2015). The innovation process and management needs of technological process innovations in core production processes (referred to in this study as RMTIs) are different from those in other enabling manufacturing processes (Milewski et al., 2015). The present study focused on RMTIs and technology process innovations and excluded other enabling operations in manufacturing plants.

Previous studies on process innovations (Simms et al., 2021; Reichstein & Salter, 2006) and manufacturing process development (Kurkkio et al., 2011) are relevant and informative for a study on RMTIs, and empirical studies on these topics cover RMTIs, among other types of process innovations. In addition, previous studies on radical innovations in general (Frishammar et al., 2016) and on radical technology innovations (Hall & Martin, 2005; Melander & Tell, 2014) are informative for studying RMTIs, although empirical research on these topics has a dominant focus on product innovations. Previous research has highlighted that innovation processes and management emphasis areas differ for product versus process innovations (Kurkkio et al., 2011; Simms et al., 2021) and for radical versus incremental process innovations (Kurkkio et al., 2011). Hence, there is a need for a focused investigation for a better understanding of the creation process and management of RMTIs as a unique case of radical technological process innovation.

1.2 Research Problem and Research Gaps

RMTIs are strategic projects that can have an impact on firms' core production capabilities. They are vital for renewing production capabilities, and timely investment in technology is important for avoiding business risk (Sinha & Noble, 2008). Early initiation of these projects is required to allow sufficient time for planning investments in technology equipment and to accumulate learning to realise the benefits of the implementation (Bourke & Roper, 2016). Furthermore, RMTIs need careful planning and management because their implementation creates a temporary disruption in the concerned firms' existing operations and because the information needed for their implementation is spread among different units and experts within and outside the firm, such as in equipment supplier firms (Ahlskog et al., 2017; Linder & Sperber, 2019, Rönnberg-Sjödin et al., 2016; Rösiö & Bruch, 2018, Simms et al., 2021).

Managing RMTI projects is challenging for manufacturing firms and their managers. Managers need to find optimal ways of collaborating within and across organisations to achieve the needed integration of manufacturing and equipment supplier firms' knowledge (Ahlskog et al., 2017; Stock & Tatikonda, 2004). Manufacturing firms need to overcome knowledge problems such as uncertainty, equivocality, complexity and ambiguity in managing RMTI projects (Simms et al., 2021), and often experience delays, budget overruns (Rönnberg-Sjödin et al., 2016) and failure to obtain the desired benefits from technology implementation (Brown, 2001). Therefore, manufacturing firms need a deeper understanding of RMTIs, their overall innovation process and managers' practices for successfully generating and implementing innovative ideas.

RMTIs involve the amalgamation of process innovation at the manufacturing firm and product innovation obtained from the equipment supplier firm (the needed technology equipment). Both are needed as part of the full concept and implementation of the RMTI idea. Previous studies have largely studied product and process innovations linked to RMTI separately (see Figure 1). They have covered processes for creating new equipment (*products*) from the perspective of equipment supplier firms (Adrodegari et al., 2015; Damanpour & Wischnevsky, 2006) and mainly the process of developing new *process* knowledge (Kurkkio et al., 2011; Lim et al., 2006) and the process of new technology adoption and implementation from the perspective of manufacturing firms (Damanpour & Wischnevsky, 2006; Milewski et al., 2015). However, the needed equipment (product) and the manufacturer's new process are closely intertwined, and this holistic and integrative view of RMTI creation remains insufficiently understood from previous research. Manufacturing firm's own product innovation processes are also interlinked and interface with their RMTI creation process (Lim et al., 2006). In this study, we focus on deeper understanding of RMTI creation processes, and do not cover its links with product innovation processes within manufacturing firms.

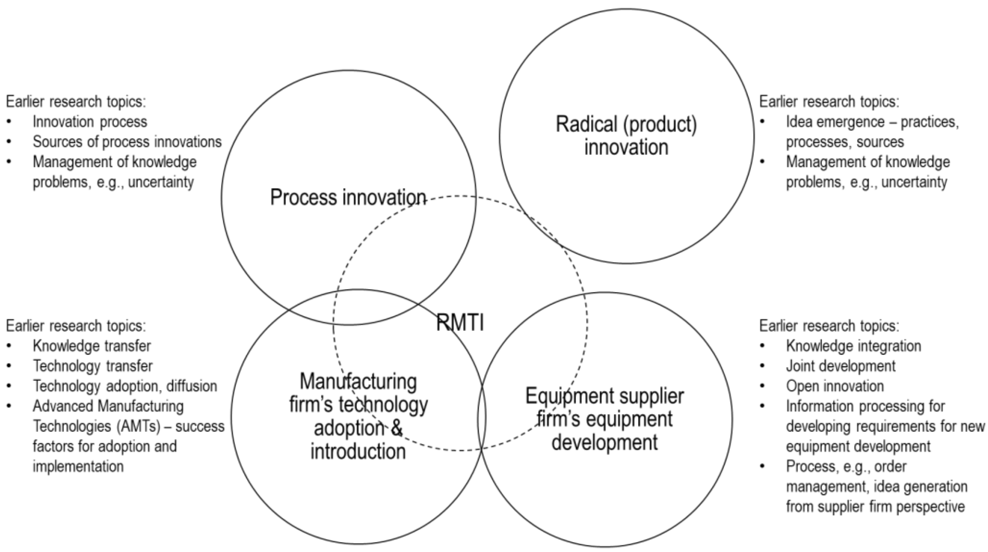

Figure 1. Positioning of this dissertation: Research domains and perspectives in the study of radical manufacturing technology innovations

Empirical studies on innovation process models for RMTI covering the entire creation process from manufacturing firms' perspective are scarce. Process models covering both product (new technology equipment) and process (implementation of new processes using a new technology) innovations remain confined to conceptual studies (Lager & Frishammar, 2010; More, 1986). The dominant empirical focus in previous manufacturing technology adoption studies has been on a group of computerisation-based manufacturing technologies called advanced manufacturing technologies (AMTs) (Baldwin & Lin, 2002; Bourke & Roper, 2016; Ellingsen & Aasland, 2019). AMTs are mainly new to the manufacturing firms adopting them, and the studies highlight manufacturing firms' tasks of decision-making, preparation (e.g. training) and implementation of the new technology (Baldwin & Lin, 2002; Bourke & Roper, 2016; Burcher et al., 1999; Ellingsen & Aasland, 2019; Sohal et al., 2006; Spanos & Voudouris, 2009; Udo & Ehie, 1996; Zammuto & O'Connor, 1992). On the other hand, RMTIs with higher levels of newness and that lack ready technology solutions and knowledge from equipment supplier firms have been less investigated. The few prior studies highlight the challenges involved in their idea and concept development at the front end, before the decision-making phase in an investment project (Simms et al., 2021) and during the development of the needed technological equipment (Rönnberg-Sjödin et al., 2016; Rösiö & Bruch, 2018). Many of these studies on high-novelty RMTIs however reflect the perspective of equipment supplier firms on the development and marketing of successful new product (new equipment) innovations (Baptista, 2013; More, 1986; Terwiesch et al., 2005). The tasks and processes involved in creating RMTIs with different levels of novelty (e.g. mainly new to the manufacturing firm versus new to the world) remain less investigated and understood from the perspective of manufacturing firms.

RMTIs have been predominantly investigated in studies on technology adoption and implementation. However, as innovations, they comprise a wider set of tasks from the perspective of manufacturing firms, beyond adoption decision-making, preparation and implementation. Process models for RMTI creation in manufacturing firms, especially those covering the important early stages of idea emergence and concept development and for RMTIs with different levels of novelty, remain unclear from previous research. Adoption and implementation research has provided information on the practices of managers for successful planning and for overcoming the challenges involved in the decision-making and implementation phases of RMTI (Burcher et al., 1999; Martinsuo & Luomaranta, 2018; Rösiö & Bruch, 2018). Similar insights into the practices of managers in manufacturing firms at the front end of RMTIs are lacking, pointing to a need for further research (Simms et al., 2021).

1.3 Goals and Research Questions

The present study seeks further knowledge on creation processes and managers' practices for RMTIs in manufacturing firms. It particularly focuses on the knowledge gap in RMTI creation processes, beyond new technology adoption and implementation, at the front end of RMTIs with different levels of novelty covering both innovation ideas regarding manufacturing firms' processes using new technologies and the needed product innovation ideas (needed technology equipment) linked with the new technologies. The goal is to gain an understanding of the creation processes for RMTIs with different levels of novelty from a manufacturing firm–centric perspective rather than a supplier- or technology-centric perspective. A second goal is to gain an understanding of the practices of managers in manufacturing firms for managing the information search needed at the front end of these innovations, as part of bringing together the needed knowledge and information for the process and product innovation ideas, linked together as part of the overall RMTI idea. The research questions for the study are as follows:

RQ1: How do manufacturing firms create RMTIs in their core production processes?

- What kinds of processes are involved in creating RMTIs with different levels of novelty?
- What are the tasks of manufacturing firms in creating RMTIs?

RQ2: How, through what kinds of practices, do managers in manufacturing firms search for the information and ideas needed for RMTI at the front end of innovation?

1.4 Research Process and Structure of the Thesis

This study followed a sequential qualitative multi-method research design to tackle the exploratory research questions. Qualitative research is suited for studies involving the 'how' type of research question and seeking understanding of processes and practices whereby phenomena unfold (Bryman, 2012; Neesham, 2017). As the first step of the research, a literature study on RMTI creation from the perspective of manufacturing firms was carried out. As part of this, the previous research on

RMTI was mapped and analysed to formulate a holistic understanding of RMTI as a concept.

Next, a qualitative exploratory study on 23 RMTI examples from different industries involving different technologies and different levels of novelty was carried out. For every RMTI example, the full, integrated RMTI creation process, including the tasks carried out by the equipment supplier firm, was mapped. The findings revealed three types of RMTIs based on levels of novelty, three types of creation processes based on the levels of novelty and manufacturing firms' task and involvement patterns in the overall RMTI creation process. The findings highlighted the proactive involvement of manufacturing firms at the front end of innovation. This encouraged further investigation from manufacturing firms' perspective of managers' practices in the early phases of idea emergence and concept development.

In the third phase of the research, a multiple-case study was carried out in three manufacturing firms. Within each case firm, the front end of three RMTI projects was studied as nested case studies. The idea emergence and concept development for the individual projects were mapped, and the managers' actions and practices involved in these were investigated. A case study is a suitable research method for observing phenomena such as the emergence of innovation ideas in their contexts. Studying nested cases within each firm enabled mapping patterns specific to the firms and the managers' practices as part of the emergence of ideas within each firm. Comparing the findings across the case firms helped draw inferences on the patterns and practices observed in the search for the information needed for idea emergence and development. The managers were observed to play a proactive role in searching for the ideas and information needed for RMTIs. The findings revealed the managers' searches using directed versus autonomous search modes in internal and external search spaces and also covering the open versus closed search for equipment suppliers, and presented propositions for managers' selection of these search practices.

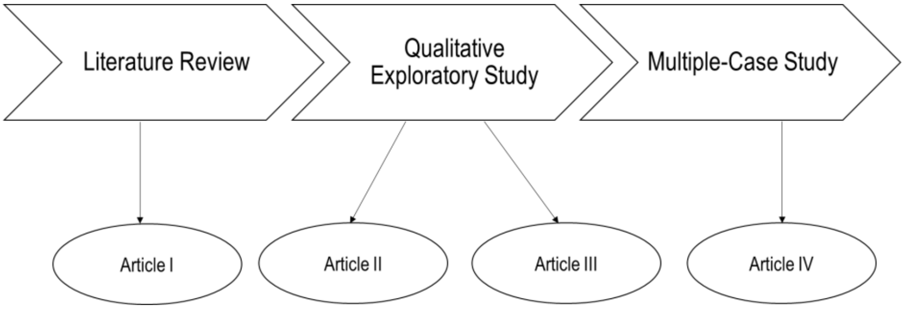

Figure 2. Research process

The analyses of creation processes and the practices of managers in manufacturing firms for creating RMTIs are presented in four focused investigations (see Table 1). Article I, 'Successful creation of radical manufacturing technology innovations', reports the results of the analysis of the literature on RMTIs. The findings summarise the previous knowledge on RMTI creation processes and managers' practices for successful RMTI management. Article II, 'Creation processes for radical manufacturing technology innovations', maps the creation processes for RMTIs with different levels of novelty, covering the phases within and between manufacturing and equipment supplier firms. The main findings of this article are the types of RMTIs based on the levels of novelty, the types of RMTI creation processes and manufacturing firms' participation patterns in all the process phases, also covering the front-end and development tasks in RMTI, in addition to technology adoption decision-making and implementation. Article III, 'Suppliers' technological newness: Source of uncertainty in manufacturing technology innovations', characterises technological newness for equipment suppliers as part of RMTI projects and the linked uncertainty experienced by manufacturing firms as part of their RMTI creation processes. The four-dimensional construct of technological newness for equipment supplier firms and the four kinds of linked uncertainties experienced in RMTI projects form the core findings of this analysis.

Table 1. Contributions of the four research articles to the research questions and goals

Research question	Article I	Article II	Article III	Article IV
Radical manufacturing technology innovation (RMTI) creation process	x	x	x	x
Manufacturing firms' tasks related to RMTI creation	x	x	x	x
Information search practices of managers in manufacturing firms for the emergence of RMTI ideas	x			x

Article IV, 'Managers' search practices at the front end of radical manufacturing technology innovations', reports the results of a multiple-case study on managers' actions and practices involved in the emergence of RMTI ideas in manufacturing firms. The findings illustrate the proactive search practices of managers for needed ideas for RMTI. Propositions are presented concerning managers' selection from among alternative search modes, search spaces for needed information and supplier search practices as part of the front end of RMTI.

The rest of the dissertation is structured as follows. The next section introduces RMTIs and gaps in existing knowledge on processes and practices for their creation. Section 3 describes the research design and research process of the study. Section 4 presents the key findings from the research concerning types of RMTI, types of RMTI creation processes, four-dimensional construct of equipment supplier's technology newness and linked uncertainty in high-novelty RMTI projects, and patterns of managers' search practices for information needed in idea and concept development for RMTIs. Based on the main findings from the study, Section 5 addresses and answers the research questions of the dissertation. Finally, Section 6 sums up the main contributions from the study to theory and implications for managers and future research.

2 LITERATURE REVIEW

2.1 Radical Manufacturing Technology Innovation

2.1.1 Definition and Nature of Radical Manufacturing Technology Innovation

RMTIs involve the introduction of a new technology into the core production process in a manufacturing firm. The core production technology is a strategic choice for the manufacturing firm, is tightly linked to the product and possibilities for future product innovation, and has an impact on customers (meeting their preferences, needs and expectations from the product). RMTIs are thus distinct from innovations in enabling technologies in a production plant, such as technologies used for material transfer, information transfer, quality control and production planning (Barth & Koch, 2019; Zelbst et al., 2012).

RMTIs are distinct from continuous production development projects due to their higher degree of newness as they involve a step change (often discontinuous) to the method of manufacturing (Keupp & Gassmann, 2013; Maine et al., 2014; Oke et al., 2007; Raymond & St-Pierre, 2005; Reichstein & Salter, 2006). They are also distinct from organisational, non-technological radical process innovations (Parikh & Joshi, 2005) due to the element of external technology introduction (Milewski et al., 2015; Stock & Tatikonda, 2004), which involves collaborative efforts with external equipment supplier firms to develop and introduce new technology equipment in their production. New process technology equipment often requires large investments. The above characteristics make RMTI an important kind of process innovation project (see Figure 3).

Studies suggest that innovation processes differ between radical and incremental process development projects (Kurkkio et al., 2011) and between core and enabling processes in manufacturing plants (Milewski et al., 2015). In the present study, we endeavoured to gain a better understanding of the nature of and innovation processes involved in RMTIs and exclude other types of manufacturing technology innovations.

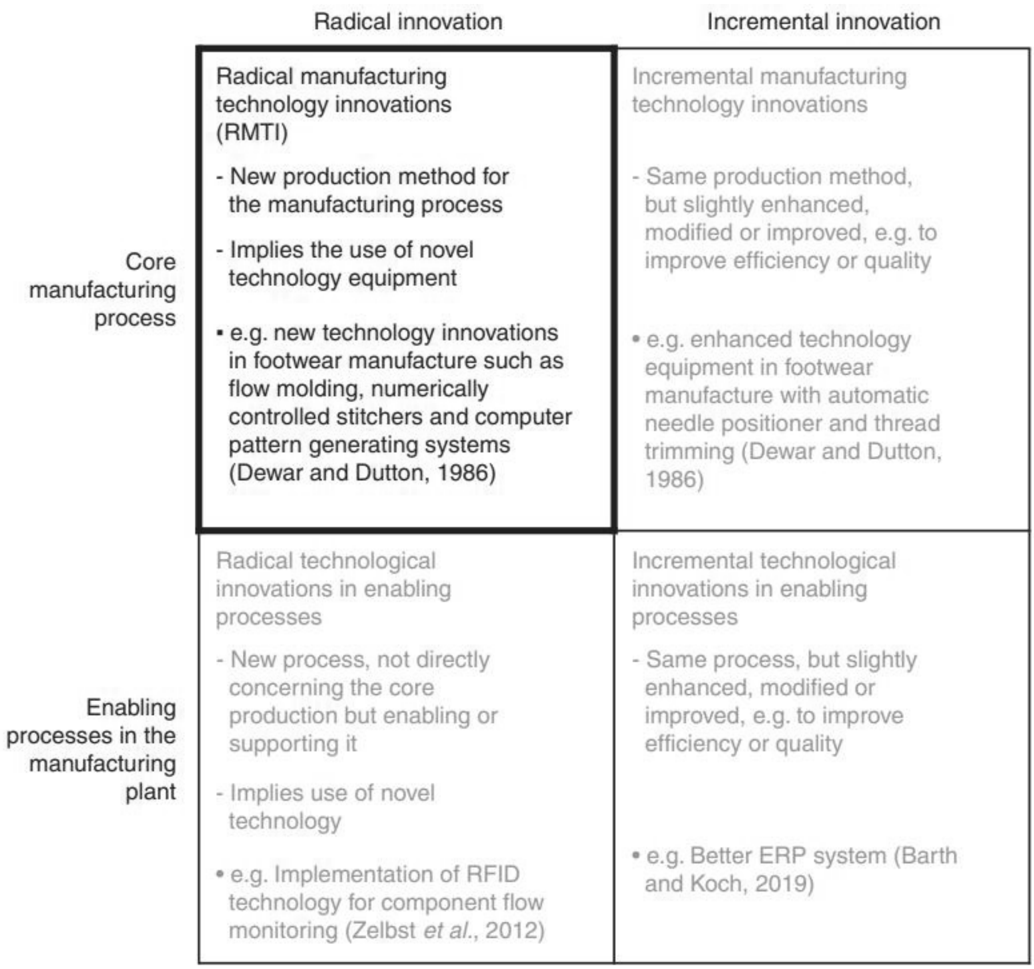

Figure 3. Technological innovations in manufacturing and positioning of radical manufacturing technology innovations therein (figure originally published in Article II)

2.1.2 Radicalness: Degrees and Types of Novelty

Studying radical innovations calls for confronting the conceptual question of what is radical and what is not. Production development projects can be seen along a continuum between two ideal types: process improvements, which involve slight adjustments within the existing manufacturing method, and the other extreme of process innovation, which involves introducing a new manufacturing method (Frishammar et al., 2013; Kurkkio et al., 2011). Process innovations can be further distinguished based on the degree of newness involved: incremental process innovations involve less novelty, such as a slightly different approach within the same method, whereas radical process innovations involve high novelty, such as a completely different manufacturing method (Dewar & Dutton, 1986; Reichstein & Salter, 2006). RMTIs fall on the extreme end of the continuum of production development projects, where there is a high degree of newness from the perspective of the concerned manufacturing firm and its existing manufacturing method (Baldwin & Lin, 2002; Stock & Tatikonda, 2004; Tyre & Hauptman, 1992).

RMTI projects may be further distinguished based on whether they are also new at the level of the industry or the world (Reichstein & Salter, 2006). Studies differ in whether they define newness at the level of the industry or the world (Oke et al., 2007; Reichstein & Salter, 2006) or at the level of the adopting firm or individuals (Ahlskog et al., 2017; Damanpour & Wischnevsky, 2006; Frambach & Schillewaert, 2002). Scholars have highlighted the need for a categorisation system for RMTIs with different levels of novelty to address the difficulty of categorising RMTIs that lie in the grey area between the new-to-firm and new-to-world extremes (Lager, 2002; Sergeeva, 2016; Reichstein & Salter, 2006). Studies have shown that innovation processes for RMTIs with new-to-world technologies differ from those for RMTIs involving technologies new mainly to the manufacturing firm (Lim et al., 2006; Linton & Walsh, 2008). These issues suggest the need for a deeper understanding of the creation processes for RMTIs with different levels of newness from the perspective of manufacturing firms.

2.1.3 Radical Manufacturing Technology Innovations: Product *and* Process Innovations

RMTIs involve the introduction of new equipment as part of implementing a new technology in the production process. Typically, equipment supplier firms are involved as key partners in these projects. On occasion, the manufacturing firm itself may develop the needed equipment (see examples in Milewski et al., 2015; Von Hippel & Tyre, 1995), but this is rare due to the complex and sophisticated nature of new technology equipment, which calls for expertise and knowledge outside the scope of manufacturing firms (Lager & Frishammar, 2010; Rönnberg-Sjödin et al., 2016). In the simplest cases, the needed technology and equipment may be ready and available from equipment suppliers who may have previously supplied the technology to other manufacturing firms (Rönnberg-Sjödin, 2013). At times, however, higher-novelty RMTI projects may require technology and equipment development, and these projects require close collaboration and joint development efforts between equipment suppliers and manufacturing firms (Appleyard, 2003; Rönnberg-Sjödin et al., 2016).

RMTI projects involve both product innovation by an equipment supplier firm (the new technology equipment needed for implementing a new technology) and process innovation by a manufacturing firm linked with the new technology. Equipment suppliers' product innovations may be intended for specific manufacturing firms or generally, for the market (More, 1986; Winter & Lasch, 2016). From manufacturing firms' perspective, the information needed for both the product *and* process innovations linked with an RMTI needs to be gathered and integrated (Ahlskog et al., 2017; Antonelli, 2006).

2.2 Radical Manufacturing Technology Innovation Creation Process

The overall RMTI creation process consists of three broad phases: the front end, equipment development and implementation (preparation, installation and start-up) of the new processes (Lager & Frishammar, 2010). At the front end of the innovation process, the RMTI idea and concept emerge and are developed to enable decision-making (go/no go) on whether to carry out the needed development work to implement the RMTI idea (Frishammar et al., 2013). At this stage, manufacturing firms often identify equipment supplier firms and set up a project for new technology equipment procurement, development and implementation (Stock & Tatikonda, 2004). The subsequent development phase involves engineering, construction and testing of the needed equipment and technology solutions (Adrodegari et al., 2015; Rönnberg-Sjödin, 2013). Finally, as part of the implementation phase, the equipment is installed at the manufacturing firm, followed by trials of the new process and ramp-up of production using the new technology (Milewski et al., 2015; Von Hippel & Tyre, 1995).

Previous research on RMTI creation processes has largely investigated the product and process innovation processes linked with RMTI separately (see Table 2). Empirical studies on the creation of new-to-industry or new-to-world production technologies or equipment are also rare (Lim et al., 2006), and this is one reason why the overall creation process involving both process innovation and the linked product innovation has remained confined to conceptual RMTI process models (Lager & Frishammar, 2010). More often, empirical studies related to RMTI have focused on within-adopter organisation newness and analysed technological and organisational adaptation issues in this context (Milewski et al., 2015). As such, RMTIs have been mainly understood as technology adoption decisions and technology implementation tasks from the perspective of manufacturing firms (Damanpour & Wischnewsky, 2006; Ellingsen & Aasland, 2019; Milewski et al., 2015; Stock & Tatikonda, 2004; Tyre & Hauptman, 1992). The creation and generation of linked product innovation (new technology equipment) has been studied separately in studies on equipment development, particularly from the perspective of equipment supplier firms (Adrodegari et al., 2015; Baptista, 2013; More, 1986; Rönnberg-Sjödin, 2013; Terwiesch et al., 2005; Von Hippel, 1978).

Table 2. Previous research on radical manufacturing technology innovation (RMTI) creation processes

Study	Focus	RMTI process model
Damanpour & Wichnevsky, 2006	Two subprocesses within the equipment supplier and the manufacturing firm	*Innovation by generation (equipment supplier firm):* recognition of opportunity > research > design > commercial development > marketing *Innovation by adoption (manufacturing firm):* initiation > implementation
Lager & Frishammar, 2010	Two subprocesses within the equipment	*Development of process technology/equipment:*

	supplier and the manufacturing firm	fuzzy front end > product development > manufacturing the first kind of equipment *Operation of process technology/equipment:* purchasing > start-up > production
Kurkkio et al., 2011	Innovation front-end process from manufacturing firms' perspective	Informal start-up > formal idea study > formal pre-study > formal pre-project
Rönnberg-Sjödin, 2013	Equipment supplier firms' perspective	Pre-study at the manufacturing firm > purchase negotiation for equipment and development > assembly and installation > start-up
Adrodegari et al., 2015	Equipment supplier firms' perspective	Quotation and order management > technical and commercial development > design > purchase > production, assembly and testing > delivery > commissioning >after-sales service, additional support activities
Milewski et al., 2015	Manufacturing firms' perspective	Ideation > adoption > preparation > installation

While both manufacturing firms' technology adoption process and equipment supplier firms' equipment development process (seen in Table 2) are relevant and informative for this study, they appear as disconnected to each other and do not offer a comprehensive view of the RMTI creation process from the perspective of manufacturing firms. Furthermore, previous studies covering RMTIs with high novelty (e.g. new-to-industry or new-to-world) are scarce (Simms et al., 2021) and cover RMTIs combined with other types of process development projects (Kurkkio et al., 2011; Milewski et al., 2015). As such, there is a lack of an in-depth understanding of the overall creation process for RMTIs with different levels of novelty from the perspective of manufacturing firms.

2.3 Radical Manufacturing Technology Innovation Creation: Tasks Involved from the Perspective of Manufacturing Firms

2.3.1 Implementation Phase

From the perspective of manufacturing firms, RMTIs imply the introduction of a new technology and its integration into the manufacturing firm's existing processes (Milewski et al., 2015; Pennings, 1987; Stock & Tatikonda, 2004; Tyre & Hauptman, 1992). In some instances, RMTI imply broader business renewal with extensive implications (Ellingsen & Aasland, 2019). Adoption decision-making (identification, assessment and selection of new technology) and implementation (preparation, installation and start-up of new process in use) are the most widely investigated tasks of manufacturing firms in RMTI projects. Previous research has extensively investigated the adoption and implementation of automation- and computer programming–based industrial manufacturing technologies called as Advanced Manufacturing Technologies (AMTs). The extensive research on AMTs during the late 20th century extended understanding on managing RMTIs beyond equipment purchase transactions, by bringing attention to the immense learning involved as part of implementing RMTIs successfully (Leonard-Barton, 1988; Voss, 1988). Recently, digitalisation and internet-based communication technologies (also included in AMTs) (Ellingsen & Aasland, 2019) and 3D printing technology (Martinsuo & Luomaranta, 2018) have also been covered by adoption research. Adoption research considers new manufacturing technology (and its product innovation) coming from outside the manufacturing firm (Pennings, 1987; Tornatzky & Fleischer, 1990). The task of manufacturing firms is to make technology adoption decisions and to implement the new technology (Damanpour & Wischnevsky, 2006). Thus, adoption research perceives that manufacturing technologies and equipment already exist and that the task of manufacturing firms is to investigate their respective process innovation opportunities by utilising them. Accordingly, the research presents an understanding of the success factors and challenges involved in the adoption decision-making and implementation of new manufacturing technologies (AMTs in particular).

Adoption decision-making: Previous research on new manufacturing technology adoption highlights the challenge for manufacturing firms in making an adoption decision on a new-to-firm technology. Technological newness for a manufacturing firm means a lack of knowledge and skills for understanding and evaluating the new technology and its use in the firm's production process (Stock & Tatikonda, 2004; Tyre & Hauptman, 1992). Martinsuo and Luomaranta (2018) observed small and medium-sized enterprises' challenges in evaluating the new 3D printing technology due to their lack of in-house experts who understood the technology and how to use it. Baldwin and Lin's (2002) study on Canadian manufacturing firms' adoption of AMTs revealed that besides information-related challenges, adoption decision-making involves overcoming challenges related to cost, institution, labour and organisation. In addition, some technologies are more systemic, so their adoption relies on other existing assets and infrastructure within the firm (Sohal et al., 2006) and even outside the firm (Ellingsen & Aasland, 2019; Martinsuo & Luomaranta, 2018). Van Lancker et al. (2016) emphasised the multi-partner, multi-dimensional nature of the changes required as part of systemic radical innovations; thus, adoption decision-making for such technologies is a more complex process.

Implementation of the new process: Mutual adaptation of a new technology and organisation is a key task that is part of new technology implementation (Milewski et al., 2015). A key objective is to achieve a fit between the technology and the organisation (Antonelli, 2006; Pennings, 1987; Von Hippel & Tyre, 1995). The technology equipment needs to meet the requirements of the product and production process and be adapted to the process requirements (Antonelli, 2006; Milewski et al., 2015). A nuanced understanding of the needed adaptations in the equipment is gained by capturing the process requirements from the operators and users (Rösiö & Bruch, 2018), small-scale experiments and pilot plants (Hellsmark et al., 2016; Pisano, 1996) and continuing to determine the requirements during the initial use of the technology in production (Von Hippel & Tyre, 1995).

RMTIs present technological newness for manufacturing firms and their technology users, and an important task for firms as part of introducing the new technology is to accumulate knowledge and learning regarding the new technology and its use (Tyre & Hauptman, 1992). The training of users to develop in-house skills in using the technology and good communication between departments and management are among the key success factors for implementation (Baldwin & Lin, 2002; Burcher et al., 1999; Lewis & Boyer, 2002; Udo & Ehie, 1996). Close collaboration with and knowledge transfer from equipment suppliers are key enablers of implementation success for technologies that present high novelty and uncertainty to the manufacturing firm (Stock & Tatikonda, 2004). Besides technology novelty, the new technology can require a shift in organisational routines and systems, if it significantly differs from their previous technology used (Tyre & Hauptman, 1992). Lack of previous similar technologies can create challenges for the implementation of a new technology (Sohal et al., 2006) as the firm needs to adapt itself to fit with the new technology (Milewski et al., 2015). Some studies also show links between the organisational structure, culture and strategy and the success of AMT implementation (Lewis & Boyer, 2002; Zammuto & O'Connor, 1992). In particular, a flexible organisational culture and diverse (both flexible and controlled) values have been shown to be particularly suited for AMT implementation (Lewis & Boyer, 2002; Zammuto & O'Connor, 1992), and strategic fit, selection and planning of AMT implementation have been shown to be critical success factors for successful implementation (Brown, 2001).

A major area of concern in the successful management of AMT implementation is whether the concerned manufacturing firm will gain the full benefits of the technology adoption, such as the improved performance of the plant or the considerable market impact of the adoption of the new technology in manufacturing (Bourke & Roper, 2016; Lewis & Boyer, 2002). It has been found that the impact of new technology implementation can be achieved subsequent to significant learning period after the new technology is implemented (Bourke & Roper, 2006). Other studies pointed to the basic misfit of AMTs to all kinds of manufacturing settings (Brown, 2001), and some studies attributed the failure to gain benefits from a new technology to manufacturing firms' lack of capability in effectively using it (Lewis & Boyer, 2002; Udo & Ehie, 1996).

2.3.2 Development Phase

Previous studies on equipment development from the perspective of equipment supplier firms have illustrated the equipment development, sales management and product lifecycle management processes from that perspective (Adrodegari et al., 2015; More, 1986; Rönnberg-Sjödin, 2013; Von Hippel, 1978). Equipment supplier firms need to collaborate with manufacturing (user) firms to generate ideas for successful equipment (product) development and to understand all the requirements of equipment development (Appleyard, 2003; Rönnberg-Sjödin, 2013; Rönnberg-Sjödin et al., 2016; More, 1986; Terweisch et al., 2005; Von Hippel, 1978). Rönnberg-Sjödin et al. (2016) investigated the effectiveness of different modes of collaborating with manufacturing firms (involvement of end users versus joint problem-solving) to address different types of knowledge problems (uncertainty and equivocality) related to the new equipment development process. While these studies pointed to the importance of collaboration with manufacturing firms for successful equipment development, they predominantly emphasised the perspective of equipment supplier firms in the equipment (product) development task.

Manufacturing firms have important roles in identifying and communicating the requirements, needs and specifications of equipment (Bruch & Bellgran, 2012; Rösiö

& Bruch, 2018), and in some cases, they also participate in the development of the actual equipment (Rönnberg-Sjödin et al., 2016). There is a need to further understand manufacturing firms' participation and practices in bringing in the needed equipment (product) as part of their new process implementation. Previous research has investigated the challenges involved during the process from the perspective of equipment supplier firms, and there is a need to cover the perspective of manufacturing firms more in this regard.

2.3.3 Front-End Phase

The front end of innovation refers to the initial phase of innovation, involving idea emergence and concept development (Kurkkio et al., 2011; Frishammar et al., 2013; Simms et al., 2021). Front end is an important phase for innovations as it is where ideas emerge, are selected for development and evolve into full concepts for the innovations. However, previous research on the front end of radical process innovations is scarce (Simms et al., 2021). The knowledge in the existing literature is limited to the processes involved in developing the full process concept and definition (Kurkkio et al., 2011; Frishammar et al., 2013), whereas how ideas for RMTI emerge in manufacturing firms remains unclear (Linder & Sperber, 2019).

Manufacturing firms typically conduct a pre-study on potential RMTI ideas before deciding to start an investment and equipment procurement/development project (Rönnberg-Sjödin, 2013). The main task during this phase is to collect sufficient information and make feasibility assessments to develop a comprehensive understanding of the potential RMTI idea, including a plan for its implementation (Frishammar et al., 2013). This enables evaluating the RMTI idea, including its implementation feasibility, risks and costs, and making a go/no-go decision on the needed investment and development project at the end of this phase (Frishammar et al., 2013).

Previous research has covered the processes and activities at the front end of RMTI and illustrated the nature of the tasks involved in it from the perspective of manufacturing firms. An idea for RMTI emerges in informal activities and conversations of managers and experts in production development, and goes through formal idea study, informal pre-study and a formal pre-study project (Kurkkio et al., 2011). Activities such as literature review, testing of the process at different scales, anticipation of product changes, definition and refinement of the process concept, risk and feasibility analyses and project planning are conducted during these phases (Kurkkio et al., 2011). In practice, however, the process of idea and concept development does not follow the above phases in a linear, uninterrupted flow, and the large number of unknowns (particularly for higher-novelty process ideas) makes the process iterative and requires revisiting previous steps and developing the idea through a trial-and-error process and experimentation (Lim et al., 2006; Kurkkio et al., 2011). Simms et al. (2021) observed the practices of managers that could enable overcoming knowledge problems at the front end by addressing the sources of knowledge gaps.

While the above studies were informative on the innovation process, activities and nature of the process, they mainly covered the development of the new process idea and concept, whereas the needed equipment (product) innovation linked with the RMTI and its concept development is not sufficiently understood from them. In addition, as Simms et al. (2021) emphasised, there is a need for further research on the practices of managers for the successful management of idea and concept development at the front end of radical process innovations. The front end of high-novelty RMTIs involves a complex information-processing and knowledge integration task for manufacturing firms as the needed knowledge and information are divided between manufacturing firm experts and equipment supplier firm experts (Ahlskog et al., 2017; Rönnberg-Sjödin et al., 2016). Knowledge integration and information processing as part of idea development occur at the level of individuals (Ahlskog et al., 2017), and there is hardly any research and previous knowledge on the practices at the level of individuals in manufacturing firms that enable and support them in this task.

2.3.4 Manufacturing firms' tasks in creating radical manufacturing technology innovations

Table 3 summarises the previous knowledge and knowledge gaps on the tasks involved in RMTI creation from the perspective of manufacturing firms. The gaps in the previous knowledge are linked with the dominant focus in previous research on manufacturers as technology adopters and on RMTIs that are new mainly to manufacturing firms. Beyond these tasks investigated in previous research, manufacturing firms' tasks in relation to the emergence of RMTI ideas are crucial at the front end of innovation, and there is a need for deeper knowledge of these tasks

(Ahlskog et al., 2017; Linder & Sperber, 2019). In addition, manufacturing firms' task in bringing in the needed equipment (product) as part of the RMTI is poorly understood from previous research. Questions like how supplier firms are identified for high-novelty RMTI projects (where there are no ready and known suppliers having ready equipment technologies) and how their knowledge accumulation and readiness for the development project influences the RMTI project and manufacturing firms' tasks in it remain unanswered in previous RMTI research.

Table 3. Tasks involved in radical manufacturing technology innovation (RMTI) creation from the perspective of manufacturing firms

Innovation process phase	Examples from the literature	Key findings on the tasks involved from the perspective of manufacturing firms	Knowledge gaps
Front end	Ellingsen & Aasland, 2019 Frishammar et al., 2013 Kurkkio et al., 2011 Martinsuo & Luomaranta, 2018 Simms et al., 2021	- Pre-study on technology and its implementation, including process and technology development for high-novelty RMTIs - Bringing together the needed stakeholders for systemic innovations - Decision-making, including all-round feasibility evaluation and investment plan	- The emergence of RMTI ideas and the tasks involved in it for manufacturing firms - The tasks involved at the front end of high-novelty RMTIs in which there is no readily available equipment from equipment supplier firms (e.g., identifying equipment supplier firms)
Development	Rönnberg-Sjödin et al., 2016 Rösiö & Bruch, 2018	- Contributing information on the requirements for developing specifications for equipment development - Participating in joint problem-solving	Manufacturing firms' tasks in relation to bringing in the needed equipment (product) as part of the RMTI creation process (e.g., development phase for RMTIs with different levels of novelty, and how manufacturing firms experience and support the development of equipment also new to the supplier firms)
Implementation	Bourke & Roper, 2016 Von Hippel & Tyre, 1995	- Start-up of new process - Resolving technical problems in equipment and process - Achieving full integration of technology and resolving organisational problems - Training, learning to use the new technology	The tasks involved in the implementation of high-novelty RMTIs from the perspective of manufacturing firms

2.4 Managers' Search Practices for Radical Manufacturing Technology Innovation Ideas

Managers have an important role in managing the front end of and implementation project for RMTIs. The front end of RMTIs involves overcoming various knowledge problems, and managers must bring together the needed resources and support for RMTI idea and concept development (Simms et al., 2021). The decision-making for investing in a new technology calls for careful investigation and planning to ensure technology fit and feasibility and good business returns from the RMTI. As part of this, managers collect and analyse information on markets, production, products and future needs and prepare a detailed plan for the RMTI implementation considering all these (Frishammar et al., 2013). Managers also need to coordinate and control the information flows needed for design and development work (Bruch & Bellgran, 2012; Rösiö & Bruch, 2018). As part of introducing the new process into use in production, managers must manage the organisation, technology and systemic change involved in the implementation of RMTIs (Milewski et al., 2015).

Previous research has broadly investigated managers' practices in decision-making regarding AMTs (Farooq & O'Brien, 2010; Small & Chen, 1995) and in their successful implementation (Burcher et al., 1999; Lewis & Boyer, 2002; Udo & Ehie, 1996). In a recent study, Simms et al. (2021) investigated managers' practices for overcoming knowledge problems at the front end of RMTIs. They highlighted the dearth of studies on managers' practices at the front end of radical process innovations. In particular, the emergence of RMTI ideas in the innovation front end remains poorly understood (Linder & Sperber, 2019). Table 4 lists the few previous studies that covered managers' practices at the front end of RMTIs (among other types of process innovation). Studies on managers' search practices for ideas for radical product-related innovations are also reviewed as a starting point for further enquiry into managers' information search practices in the specific case of RMTIs.

Table 4. Previous research on managers' search practices at the front end of radical innovation

Study	Description	Main findings
Previous research on managers' practices for the search for and development of radical manufacturing technology innovation ideas		
Kurkkio et al., 2011	Multiple-case study in four firms in the mineral industry	The front end of radical process development projects involves top-management initiative and a formalised structure.

Study	Description	Main findings
Frishammar et al., 2013	Multiple-case study in four firms in the mineral industry	Managers' practices for reducing uncertainty as part of developing the process definition at the front end
Ahlskog et al., 2017	Longitudinal case study on new manufacturing technology development	Three knowledge integration processes are used by manufacturing firm experts in novel manufacturing technology development: capturing knowledge from equipment supplier firm experts, joint learning with them and absorbing learning within manufacturing firm.
Terjesen & Patel, 2017	Survey of 505 firms spanning 23 manufacturing industries in the UK	Search depth, involving external search at few sources with which the manufacturing firm has close relationships, is positively linked with process innovation outcomes.
Linder & Sperber, 2019	Community Innovation Survey, Italy	Internal knowledge within manufacturing firms is a valuable source of knowledge for generating radical process innovation ideas.
Simms et al., 2021	Multiple-case study in six food-processing firms in the UK	Four types of knowledge problems exist at the front end of radical process innovations. Managers practice appropriate responses to these knowledge problems based on the sources of the problems.
Previous research on search practices for radical innovations		
Rice et al., 2001	Longitudinal study of eight radical innovation projects in six large firms	Radical innovation ideas emerge at the level of technical experts within firms. However, these individuals face challenges in initiating the innovation process.
Reid & de Brentani, 2004	Literature review and conceptual model for the emergence of radical innovation	Radical innovation ideas emerge in individual-level autonomous search processes.
Chiang & Hung, 2010	Survey with 184 Taiwanese electronic-product manufacturers	External search at a wide breadth of external sources is linked with emergence of radical innovation ideas.
Sofka & Grimpe, 2010	Survey of over 5,000 firms from five European countries	Search from external sources is an effective strategy for innovations involving novel technologies in technologically advanced environments.
Aloini et al., 2013	Literature review, 80 case studies and questionnaire survey among 500 high-technology firms in Italy	For discontinuous innovation ideas, firms need to combine external search practices with internal practices for idea generation and management.
Nicholas et al., 2013	Survey of 107 companies in Ireland	Search strategies used for seeking radical innovation ideas
Melander & Tell, 2014	Case study on a collaborative new product development project	Uncertainty in the selection of a supplier and its associated technologies has an impact on the selection process and outcomes.
Acar & Van den Ende, 2016	Survey of 230 science contest participants	Individual-level search efforts and practices (deep search versus wide search in new knowledge domains) are linked with emergence of radical ideas.
Kennedy et al. 2017	Case study of the innovation process for a radical new product	The innovation process for sustainability-oriented radical innovations involves strategy-led directed search for ideas. It involves five linked practices.

Study	Description	Main findings
Rhee & Leonardi, 2018	Survey of communication networks at a software company	Individuals with constrained networks produce ideas through interrogation logic, whereas individuals with less constrained networks generate good ideas through recombination logic.
Wiener et al., 2020	Case study in two companies in Austria	Firm culture has an impact on whether external sources can be involved in the generation of innovation ideas.
Oltra et al., 2022	Case study of a skunkworks project at PSA Peugeot-Citroën	Skunkwork/autonomous radical idea development is facilitated by distinct human resource management practices.

Radical innovation ideas emerge through problem-solving processes at the levels of individuals and teams (Frishammar et al., 2016). Individuals and teams engage in the search for novel ideas through directed (top management–led) or autonomous (self-driven) processes. Studies covering product-related radical innovations (Pihlajamaa, 2017; Reid & de Brentani, 2004; Rice et al., 2001) highlight individual-level initiatives and autonomous processes as the starting point for the emergence of radical innovation ideas. According to Reid and de Brentani's (2004) conceptual model for the emergence of radical innovation ideas in firms, technology experts' autonomous practices first draw new information to the firm from outside sources. These experts spot new information, determine its value for the firm and work to introduce it to the firm and to top management for decision-making. On the other hand, some studies also illustrate a top-down process in which top managers' practices and initiatives lead to subsequent information searches for developing ideas. For example, Kennedy et al. (2017) illustrated top managers' strategy-led initiatives as the starting point of a directed formal investigation for the search for and development of needed innovation ideas. Previous studies on the front end of RMTIs (Frishammar et al., 2013; Kurkkio et al., 2011) have observed the use of directed, formal investigations for developing RMTI ideas, whereas the use of autonomous search practices has not been noted in previous studies on RMTIs.

Equipment supplier firms are important external sources of knowledge needed to generate RMTI ideas in addition to the knowledge available internally within manufacturing firms (Ahlskog et al., 2017; Linder & Sperber, 2019). Ahlskog et al. (2017) illustrated knowledge integration processes whereby technology experts in manufacturing firms absorb and integrate knowledge from equipment supplier firms to generate novel insights for RMTI. Terjesen and Patel's (2017) study on the relationship between information search practices and process innovation outcomes indicated that a deep search for information within few select sources rather than across many different sources is linked to the emergence of novel process ideas.

Managers' search for and identification of potential equipment suppliers at the front end guide their search for information and ideas. However, search for and selection of partners for radical innovation idea development pose many challenges (Gattringer et al., 2017; Melander & Tell, 2014; Wiener et al., 2020). Melander & Tell's (2014) study on radical technology innovations highlights that the selection of a supplier–technology dyad involves many uncertainties, and the choice may not be evident at the start. In the case of high-novelty RMTIs, the knowledge and information needed for radical ideas may be found in unfamiliar suppliers from distant industries (Kalogerakis et al., 2010). Previous research on managers' practices for searching for and identifying equipment supplier firms to seek the new information needed for generating RMTI ideas has been very limited, and further research is needed.

Managers' efforts to search for relevant information are necessary to discover the right ideas needed to create a successful innovation (Acar & Van den Ende, 2016; Frishammar et al., 2016; Nicholas et al., 2013; Reid & de Brentani, 2004). Previous research on the emergence of radical innovations has emphasised the need for dedicated practices to support the emergence and initial development of novel ideas (Bessant et al., 2010) as radical innovation ideas face barriers in the early phases (Sandberg & Aarikka-Stenroos, 2014). Managers' practices for searching for the information needed to develop RMTI ideas in their early phases constitute an important knowledge gap.

3 RESEARCH METHOD

3.1 Research Design

The philosophical positioning of this research matches the critical realist paradigm (Edwards et al., 2014). Critical realism integrates a realist ontology (there is a real world that exists independently of our perceptions, theories and constructions) with a constructivist epistemology (our understanding of this world is inevitably a construction from our own perspectives and standpoint) (Maxwell, 2012). In contrast to positivist ontology, which equates reality with recordable events, and the constructionist position, which collapses ontology into discourse, critical realists adhere to a stratified or in-depth ontology (Edwards et al., 2014). It involves making a distinction between the *empirical* (what we perceive to be the case: human sensory experiences and perceptions), the *actual* (the events that occur in space and time, which may be different from what we perceive to be the case) and the *real* (the mechanisms and structures that generate the actual world, together with the empirical) (Edwards et al., 2014). Such complex, open systems call for rich, thick and explanatory research (Edwards et al., 2014).

In pursuit of a deeper understanding of the processes and practices of RMTI creation in manufacturing firms, the present study adopted a sequential qualitative multi-method research design (see Table 5). Qualitative research methods are well suited for studying innovation processes (Poole et al., 2000) as they enable deep and sensitive attention to the details of the context needed to generate answers to *what, how* and *why* types of research questions related to innovation processes (Neesham, 2017). The sequential research approach (Creswell, 2009) allowed the use of different methods and datasets for the four focused investigations (Articles I–IV) in the present study to focus on specific research questions. It also allowed to incorporate the timing and availability of access to the data needed for the research.

Table 5. Research design and contexts

	Research data	Number of firms involved	Descriptions of firms involved	Radical manufacturing technology innovation projects covered
Article I	Literature review	NA (not applicable)	NA	NA
Article II	Exploratory study	17 firms	- Revenue range: EUR6M to EUR31B - Size range: < 50 to > 10,000 employees - 14 manufacturing firms from the sheet metals, assembled machines and machine components (industrial vehicles, ship engines, valves), electric motors, generators, electronics, semiconductors, luxury goods, paper and pulp and furnace industries - 3 equipment supplier firms from the machine tools, nanotechnology and paper and pulp industries	23 projects*
Article III	Subset of exploratory study data (covering only high-novelty RMTIs)			16 projects*
Article IV	Multiple nested–case study	3 firms	**Firm A:** - Revenue: > EUR100M - Small (< 500 employees) - Semiconductor manufacturing	9 projects* (3 projects in each firm): A-1, A-2, A-3
			Firm B: - Revenue: > EUR1B - Medium (about 1,000 employees, part of a larger corporation) - Process-based manufacturing	B-1, B-2, B-3
			Firm C: - Revenue: > EUR2B - Large (about 5,000 employees, part of a larger corporation) - Assembled-product manufacturing	C-1, C-2, C-3

* Names of projects given in Tables 6 and 7

In the first step of the research (Article I), previous studies covering RMTIs were broadly searched and reviewed. The literature review indicated that the emergence of RMTI ideas remains poorly understood. Previous research from the perspective of manufacturing firms has predominantly focused on the management of challenges in adoption decision-making and implementation tasks, particularly for RMTIs that are mainly new to the adopting manufacturing firms. RMTIs have been covered, among other types of process innovations, but studies covering high-novelty RMTIs are scarce. This knowledge gap guided the next steps of the present research.

In the next step, empirical data on a wide breadth of RMTI examples with different levels of novelty were investigated. Altogether, 23 RMTI examples from 17 Finnish manufacturing firms were identified. The final dataset included a wide breadth of RMTI examples in terms of their technologies and industries. The 23 RMTI examples came from 17 firms of different sizes (from fewer than 50 employees to more than 10,000) and from different industries (e.g. equipment, assembly and process manufacturing, metals, electronics, nanotechnology, luxury goods and shipbuilding). The companies are well known, and some of the RMTI projects resulted in patents. The exploratory study also covered some equipment supplier firms because they are important participants in RMTI projects, and the purpose of this study was to obtain a holistic overview of the RMTI creation process. The data analyses focused on the innovation processes and RMTI project types (Article II) and technological newness for equipment supplier firms in high-novelty RMTIs (Article III). The findings from the exploratory study indicate that manufacturing firms participate in the early stages of the idea and concept development of RMTI projects, which involve both process innovations and linked equipment (product) innovations by supplier firms. This encouraged the next step in the research, involving an in-depth investigation of the front end of the RMTI process from the perspective of manufacturing firms.

In the final step of the research, a multiple-case study on the front end of RMTI projects in three case firms was carried out. The firms were in the semiconductor manufacturing (Firm A), process-based manufacturing (Firm B) and assembly manufacturing (Firm C) industries. With the purpose of investigating actual processes at the front end of RMTI projects in these firms and practices of the managers involved, the front end of three RMTI projects within each firm was studied. The projects enabled a holistic understanding of managers' practices at the front end of RMTIs in manufacturing firms. During the analyses of the case study data, managers' searches for unknowns came to the forefront as important in the emergence of RMTI ideas, and this matter was analysed further to arrive at the findings from the research (Article IV).

The sequential research design thus enabled the use of multiple qualitative research methods and datasets, building on specific previous studies and theoretical concepts for making inferences on RMTIs, their innovation processes and managers' practices involved in them.

3.2 Research Data

3.2.1 Literature Review

The purpose of the literature review study (Article I) was to map previous knowledge and theories on RMTIs and their creation processes and practices in manufacturing firms. Previous studies covering RMTIs were broadly searched in Web of Knowledge database using keywords *radical innovation in manufacturing technology* on 24.04.2015 which resulted in 77 articles. These were used as the starting point for identifying relevant literature using journal, author and citation search (details described in Article I). At the end of the search, 53 articles were identified for detailed review of previous research on RMTIs.

Studies in the field of technology adoption, particularly the adoption and implementation of AMTs, account for a large portion of studies focusing directly on RMTIs and taking the perspective of manufacturing firms. A small but growing body of literature on process innovations contributes few studies covering RMTIs, often among other kinds of process innovations. The literature on radical innovations does not contribute focused studies on RMTIs but concentrates mainly on product-related radical innovations. RMTIs are also featured in the technology literature related to novel manufacturing technology research and development (R&D).

3.2.2 Qualitative Exploratory Study

The purpose of the exploratory study (Articles II and III) was to map different kinds of RMTIs and to understand similarities and differences across RMTIs with different levels of novelty, their creation processes and manufacturing firms' roles and forms of participation therein. Data on a variety of RMTI examples were sought, from simple automation introduction projects to projects with process technology breakthroughs and everything in between these two extremes. The search strategies used for RMTI examples included searching and contacting firms that had active process R&D and firms that had adopted novel technologies, such as nanotechnology and additive manufacturing, which are considered topical manufacturing innovations. A more open search was also conducted by contacting production development managers and production directors in manufacturing firms and asking them about their RMTI experiences. The identification and selection of firms thus followed a purposive sampling strategy, in which the intention was to seek empirical examples serving the research interest and purpose (Bryman, 2012). More RMTI examples were searched until saturation was reached—that is, when new information and themes on RMTI creation projects no longer emerged (Guest et al., 2006; Bryman, 2012). This happened around the completion of 20 RMTI examples and data was collected on three more examples after that.

Semi-structured interviews with managers closely involved in RMTI projects were the primary method used to collect data on the RMTI examples. Such interviews were deemed a suitable data collection method as they would allow for collecting rich information on the processes involved in the studied projects. Semi-structured interviews are suitable for exploratory inquiries on poorly understood phenomena as they allow the pursuit of novel information and topics that may emerge during an interview, which may be important in understanding the phenomena being studied (Bryman, 2012). The interviews were conducted on the companies' premises, in the calm environments of conference rooms, and were recorded with the permission of the interviewees. The recordings were later transcribed. Prior to the interview, the interviewees were given the interview outline, which consisted of the main themes and questions for the interview, to set expectations regarding the scope of the interview.

A total of 23 semi-structured interviews were conducted. Table 6 presents an overview of the RMTI projects studied and the interviewees. For every project, further data were searched by requesting additional interviews with other persons closely involved in the project and requesting relevant project documents, such as reports, presentations and emails. Further information on the RMTI projects was sourced from publicly available information in the companies' newsletters, press releases and websites. The project documentation was used as secondary data to enrich the primary interview data. Confidentiality of persons' names and of the projects and documents shared during the interviews was assured to encourage free sharing of detailed information on the projects. In line with the confidentiality promise, the names of the subject firms and interviewees are not disclosed in this dissertation or in linked publications.

Table 6. Semi-structured interviews for the exploratory qualitative study

Project	Radical manufacturing technology innovation (RMTI) name	Interviewees	Duration (mins)
1 (A)	Anti-tarnish coating on silver	Production director, manufacturing firm* Production foreman, manufacturing firm Vice president, supplier firm	28 55 + 36
2	Three-dimensional (3D) printing of casting dies	Production director, manufacturing firm* Process designer, manufacturing firm	28 86
3 (B)	Industrial particle coater based on nanotechnology	Vice president, technology unit, supplier firm*	61
4 (C)	Continuous deposition process for thin films	Vice president, technology unit, supplier firm*	61
5 (D)	Flexible automation of testing tool	Head of supply chain engineering, manufacturing firm	52 +
6 (E)	Automation of large furnace	Plant manager, manufacturing firm	48
7 (F)	New process for lignin extraction as side stream in wood pulp manufacture	Head of technology, manufacturing firm Head of innovation, manufacturing firm	49 67
8	Implementation of new assembly process for electronic-device manufacture	Head of production technology, manufacturing firm	49
9 (G)	New concept for heating web in paper manufacture	Production director, supplier firm	66
10	Automation of stacking process in transformer core manufacture	Production development manager, manufacturing firm	38 +
11 (H)	Automation of large engine head assembly	Process development manager, manufacturing firm	62
12 (I)	Cheaper cutting tool for slots on the circumference of motor plates	Manufacturing manager, manufacturing firm*	65 +
13 (J)	Automation of the spot-welding process for round plates in motors	Manufacturing manager, manufacturing firm*	65 +
14 (K)	Paper pulp–making technology	Vice president, production, manufacturing firm*	49
15 (L)	Energy plant for utilisation of production plant by-products as renewable fuel	Vice president, production, manufacturing firm*	49
16	Automation of production plant	Production development manager and production foreman, manufacturing firm	40
17	Automation of production plant	Vice president, production, manufacturing firm	54 +
18 (M)	New technology in the manufacture of specialised silicon wafer	Senior process development engineer, manufacturing firm	55

Project	Radical manufacturing technology innovation (RMTI) name	Interviewees	Duration (mins)
19	3D laser technology sheet metal–cutting equipment	Chief executive officer, manufacturing firm	49 +
20 (N)	Special-purpose equipment: joining machine for large pipe flanges	Business director, supplier firm*	111
21 (O)	Special-purpose equipment: insulation machine for generator coils	Business director, supplier firm* Sales manager, supplier firm	111 35
22 (P)	Special-purpose equipment: Inductive heating–based semi-automatic joining machine for generator coils	Senior production development manager, manufacturing firm	88
23	Novel technology equipment for electronic-component manufacture	Senior production development manager, manufacturing firm	71
Alphabets (A, B, C…) indicate the data subset consisting of high-novelty RMTIs analysed in Article III. + Factory tour to visit the new process. Discussion not recorded and transcribed. Notes made. * The same interview covered two RMTI examples.			

The interview outline for exploratory study data collection (full interview outline given in Article II) focused on four main thematic sections: backgrounds of the interviewee and firm, drivers and process of emergence of the selected RMTI project, the project's development process and the project's implementation process. The interviews covered the entire creation process, from idea emergence to implementation, main events and activities, key actors involved and their roles and forms of participation, and explored core issues in the creation process (e.g. key enablers and challenges).

After the data collection and preliminary data analysis, the novelty and process categorisation frames were validated by reporting the findings to the interviewees in a practitioner-oriented report, organising a workshop to present the findings and requesting possible feedback. Changes were not requested by the interviewees at this stage.

3.2.3 Multiple-Case Study

The purpose of the case study (Article IV) was to understand the practices of the managers in manufacturing firms involved in RMTI emergence. Firms for the case study were selected from among the 17 firms in the previous exploratory study. In selecting firms for the case study, the focus was on firms that had higher numbers of higher-novelty RMTI projects. Emphasis was placed on selecting firms with more experience and multiple recent RMTI projects for mapping practices and processes in manufacturing firms for RMTI initiation and management (again following purposive logic). In addition, there was an interest in selecting firms that were quite different from each other, as is the logic for case selection in multiple cases, to enable the comparison of entirely different cases and contexts and the seeking of theoretical explanations (Thomas, 2011). The projects involved the introduction of a new process technology to a core production process and were selected by a corresponding manager in each firm. The three firms were labelled A, B, C for keeping the names of firms anonymous, while the projects within each firm were numbered 1-3. This labelling is independent of the exploratory qualitative study (Articles II, III), and the labels bear no reference to projects using alphabetical labels in Article III. The projects had been completed (implemented in production), with the exceptions of C-1, which was still in the concept development phase, and B-3, which was in the late implementation phase (installation).

Firm A is a small firm in a fast-paced market in which the future requirements of product performance jump levels above the present-day requirements. As a result, from time to time, the new product development needs exceed the limits of the present production technology (e.g. accuracy tolerance level). Projects A-1 and A-3 involved a situation in which the next jump in product development required a new kind of production technology because the present technology and method of manufacturing were not fit for making the next generation of the product. Project A-2 involved discovering a better alternative for the technology equipment and manufacturing process.

Firm B is a medium-sized firm in the forest-based product industry. The firm is an industry leader and has a strategy-driven and target-oriented culture. The strategic targets of the firm, such as increasing product yield and achieving high customer value and low (zero) environmental emissions, are reflected in all the projects described for the firm. Project B-1 involved a theoretically superior (high-yield) alternate production process; however, the process had not been popularly used in the industry, and there had been many studies on it. As part of the strategy planning process, the technology was chosen for deeper investigation. Projects B-2 and B-3 involved adding new steps to the core production process for generating sustainable fuel (thereby replacing fossil fuel) and considerably reducing effluent emissions to the environment, respectively. For these two projects, there were no ready, proven solutions or processes known from the outset.

Firm C is a very large firm that makes tailored special business-to-business machinery products, with varying sizes of individual orders. The production process details are planned on a per-order basis. If the product specifications or order size (volume) requires special tools, these are made part of the delivery-project budget; thus, there is room for procuring special-purpose smaller tools for individual projects. The problems and inefficiencies of highly customised production encourage a culture of seeking ideas for improved production speed and cost savings in local teams. Project C-1 involved a radically different approach to shaping the material into its product form: using bending as the approach instead of the present concept of cutting and joining. This had implications for the materials that could be utilised, such as their cross-sectional profiles and the core production processes and their technology equipment. Projects C-2 and C-3 involved known superior process technologies (popular in mass production applications), which needed clever ideas to fit them into the complex product mixes and batch sizes of their production context. This implied a shift to using an alternate production technology, replacing the initial slower production process.

As part of the case study data collection, 17 semi-structured interviews were conducted, and nine RMTI projects were covered (Table 7). Secondary data consisting of project documents, emails and presentations were collected or seen during the interviews. For every project, all the key persons involved in the initial phase/front end of the project were requested to participate in the interviews. Exceptions were Project B-2 (manager involved in detailed concept development unavailable), Firm A and C projects (purchase manager unavailable) and Firm C projects (top managers unavailable). Equipment supplier firm managers were purposely excluded from the data collection because our interest was in capturing manufacturing firms' internal practices. Three online interviews were conducted due to the interviewees' distant locations. The interviewees in the final dataset were mainly top and middle-level managers giving the study its scope of focusing mainly on the perspective of managers in manufacturing firms involved in RMTI idea and concept development.

Table 7. Semi-structured interviews for the multiple-case study

Project	Project description	Interviewees	Duration (mins)
A-1	Introduced a new technology that would enable higher accuracy in certain product features beyond those enabled with the	Senior development manager, technology	71 65

Project	Project description	Interviewees	Duration (mins)
	previous technology and tool (needed to make a next-generation product)	Senior process development engineer Senior vice president, products*	114
A-2	Introduced a new technology and tool that would enable a neat finish on certain product features compared to the existing technology and tool, which left a crude finish (customers complained of an imperfect finish)	Process engineering manager Senior vice president, products*	100 114
A-3	Introduced a new process approach and linked tool for generating a higher-performance semiconductor raw material (needed to make next-generation products)	Process engineering manager Senior vice president, products	63 114
B-1	Introduced a new chemical process and the equipment needed to achieve the same product from raw materials with higher yield and quality (to meet the company's strategic production development targets)	Senior vice president, production mills* Senior vice president, business development* Vice president, key accounts and technical customer service Vice president, mill manager* Vice president, mill manager*	84 89 55 38 111
B-2	Introduced new processes (and related technologies and equipment) for generating renewable fuel using unique biowaste side streams to replace the previous fossil fuel–based processes	Senior vice president, production mills* Senior vice president, business development* Vice president, mill manager* Technical director, projects* Vice president, mill manager*	84 89 38 72 111
B-3	Introduced a technology for recycling and reducing the effluents released into the environment (to meet the company's strategic production development targets)	Senior vice president, business development* Vice president, mill manager Technical director, projects* Vice president, mill manager*	89 55 72 111
C-1	Introduced an alternate assembly approach (switched from cutting and joining to bending) and a linked technology to improve the process efficiency and quality	Senior research and development (R&D) engineer Senior R&D engineer Senior production development manager R&D engineer	57 47 183 53
C-2	Introduced a new process technology and related equipment to automate the previous manual process	Manufacturing manager*	76
C-3	Introduced a new tool and technology to replace the previous manual and slow process	Manufacturing manager*	76
* The same interview covered two or three radical manufacturing technology innovation projects one after another.			

The interview outline (full outline given in Article IV) included questions on the sequence of events, activities, people engaged and all efforts and considerations involved in RMTI idea emergence and concept development at the front end of the selected RMTI projects in which the interviewees had participated. The interviewees were allowed to give uninterrupted accounts of the front end of the RMTI projects as they remembered the projects. Further questions were asked to ensure comprehensive coverage of all the topics and to delve deeper into the issues that seemed central to idea emergence and concept development in each project.

The data collected via interviews were immediately reviewed, and additional information or clarification was obtained when needed. In some cases, this led to a follow-up small discussion in person or over the phone, and in a few cases, the follow-up questions were answered via email. The interview data were transcribed and read through to become closely acquainted with the data collected on the projects and firms. At this stage, open coding was conducted to identify key and interesting issues in the data. At the end of the open coding and preliminary analysis, a summary of the data generated on the projects was presented to key contact persons in the three firms to confirm the facts regarding the projects obtained through the interviews and their interpretations.

3.3 Data Analysis

The data obtained from the exploratory and case studies were analysed using an abductive approach, which involves alternately moving between the data and the literature with a constant comparative approach to arrive at theoretical comprehension (explanations) of the observations in the data (Dubois & Gadde, 2002). The abductive analytical approach is aligned with an exploratory qualitative case-based research strategy, seeking new knowledge and understanding of previously poorly understood empirical phenomena (Dubois & Gadde, 2002). Detailed data analysis steps, chain-of-evidence from raw data to the identified themes and constructs, and illustrative quotes from raw data to illustrate and exemplify the findings have been described as part of research method and findings sections in the individual articles. In this section, an overview of the data analysis approach and process is provided.

The analyses of both datasets (from the exploratory and case studies) began with the initial reading of the data, and an open coding approach was used. This step led to close acquaintance with the data. I used Atlas.ti for the exploratory study data open coding and QDA Miner Lite for the case study data open coding. At the end of this phase, I came to understand the key and interesting issues in the data, which I could pursue further for an in-depth analysis.

In line with the purpose and wide breadth of the research design for the exploratory study, the data analysis (for Article II) followed a simple analytical frame for identifying similarities and differences in the creation processes and participation of manufacturing and equipment supplier firms across the various process phases.

The further data analyses (for Articles III and IV) used thematic coding (Braun & Clarke, 2019) and in-depth analyses of emergent codes, categories and the links between them. This emergent understanding formed the basis for identifying concepts from the literature that reflected the observations and understanding emerging from the data. Once a match was identified from the literature, I tried to write an explanation of the observations in the data using previously known concepts. This led to a further analysis of issues in which the concepts fell short of coherently describing the data and patterns in the individual projects. At times, this led to a second round of literature review to identify appropriate concepts. The resulting findings involved a coherent description of the patterns seen in the projects and a discussion to understand the potential explanations for them using theoretical concepts. For the data analysis reported in Article III, one project was excluded because the information was deemed insufficient for the data analysis.

4 FINDINGS

4.1 Article I: Successful Creation of Radical Manufacturing Technology Innovations

4.1.1 Summary of Findings

Article I reviews previous research on RMTI emergence and management. RMTIs have been covered in three broad domains: literature on the adoption of AMTs in manufacturing firms, technology literature on novel manufacturing process technology R&D and literature on organisational processes for the management of process innovations. The literature review reveals a dominant technology-centric focus in previous research on RMTI, with a large portion of studies treating manufacturing firms as technology adopters. Empirical studies on the creation of RMTIs are rare. Particularly, the processes and practices of manufacturing firms whereby RMTI ideas and concepts emerge are not well understood from previous empirical research.

Table 8. Previous research on radical manufacturing technology innovations

Literature	Examples of studies	Focus areas in the literature
I. Advanced manufacturing technology adoption and implementation literature	Da Rosa Cardoso et al., 2012 Lewis & Boyer, 2002	Success factors and challenges in adoption decision-making and new process technology implementation
II. Process technology literature	Kawase, 2015	Technological developments, breakthroughs in process technologies
III. Process innovation literature	Reichstein & Salter, 2006	Organisational processes and challenges involved in creating process innovations

4.1.2 Contributions of the Article to the Dissertation

Article I introduces the RMTI emergence and management research framework for the present study. It maps the literature on RMTI emergence and management and guides the positioning of the present study in relation to previous research. It summarises previous knowledge on the topic of the dissertation and guides the following empirical research.

4.2 Article II: Creation Processes for Radical Manufacturing Technology Innovations

4.2.1 Summary of Findings

Article II presents the results of the study on the RMTI creation process for 23 empirical examples of RMTI, mapping the entire process from initiation to implementation, including the activities conducted within either the equipment supplier or the manufacturing firm or jointly between them. The findings reveal three types of RMTI projects based on the novelty level: low-, medium- and high-novelty RMTIs. Low-novelty RMTIs present newness mainly to the manufacturing firm, medium-novelty RMTIs also present newness to the equipment supplier firm and high-novelty RMTIs also present newness to the industry or the world.

The studied projects varied in the scope of the creation process, based on the novelty level. The creation process was a short procurement type for low-novelty RMTI projects, whereas in medium- and high-novelty RMTIs, the creation process involved additional phases for equipment and process technology development (Table 9). Manufacturing firms' support, interest and participation were also observed in the technology and equipment development phases, in addition to the start-up/implementation phase. The findings map the participation patterns of manufacturing and equipment supplier firms in the overall creation process. The collaboration activities moved up front for higher-novelty RMTIs compared to low-novelty RMTIs.

Table 9. Three types of radical manufacturing technology innovation creation processes

Process type	Process description
Procurement-type process	**Pre-study**: • Process conceptualisation • Technology investigation **Procurement**: • Investment planning and decisions • Investment preparation • Order equipment • Delivery, installation, trials **Implementation**: • Ramp-up • Learning to use the technology
Development-type process	**Conceptual phase**: • Process conceptualisation • Equipment concept development, including technology selection • Preparation of equipment prototypes (proof-of-concept models) **Development phase**: • Investment planning, preparation and decisions • Contract • Equipment engineering, designing • Construction, trials, possible rework • Delivery, installation • Production trials, possible rework **Implementation**: • Ramp-up • Learning to use the new technology, possible adaptations
Invention-type process	**Creation of new process know-how**: • Discovery - basic research • Application research and development (technical, lab-scale) • Discussions exploring new process application • Creation of a consortium for the development of ideas **Process concept validation**: • Equipment concept development • Proof-of-concept-level prototype, such as demo plant • Revision/improvement of process and equipment concepts **Investment consideration**: • Addressing critical areas of risk and uncertainty • Investment planning • Decision-making, negotiation, contract signing **Equipment development**: • Equipment design and engineering • Construction • Trials, possible redesign/rework • Delivery, installation • Production trials, possible redesign/rework **Implementation**: • Ramp-up • Learning to use the new technology, possible adaptations

4.2.2 Contributions of the Article to the Dissertation

Article II illustrates a wide breadth of RMTI examples with varying degrees of novelty and differences in their creation processes. The findings contribute knowledge on the creation process for RMTI from the perspective of manufacturing firms and reveal the scope of manufacturing firms' roles and activities in RMTI creation.

4.3 Article III: Suppliers' Technological Newness: Source of Uncertainty in Manufacturing Technology Innovations

4.3.1 Summary of Findings

Article III investigates the technological newness for equipment supplier firms involved in RMTI projects and how this affects manufacturing firms' RMTI creation process experience. RMTI projects with an overall higher degree of novelty also present first-time experience and technological newness for the equipment supplier firms participating in the projects. Technological newness for an equipment supplier firm as part of an RMTI project concerns one or more of the following dimensions: context newness, application newness, construction newness and technology newness. These four dimensions inform what is new to the equipment supplier firm in an RMTI project.

Table 10. Four dimensions of technological newness for equipment supplier firms in radical manufacturing technology innovation projects

Dimension	Description	Illustrative quote
Context	The surrounding environment, its processes or the location of equipment use (e.g., specific plant, plant layout, connected processes) are new to the supplier firm.	Project A: *'Of course, there are lots of different things we do to the pieces before they go to the coating machine, and they [supplier firm] don't know how that thing goes.'*
Application	The kind of use of the technology (e.g., new kind of raw material; new form of raw material or special context of use, such as at a very different scale or in a very different industry context) is new to the supplier firm.	Project K: *'The problem was that we had no experience in that kind of scale when we were implementing it, so there was a risk.'*
Construction	The way of building up the physical construction of the solution is new to the supplier firm (e.g., new subcomponents, systems, mechanisms, materials, dimensions, design, configurations and specifications of the equipment).	Project E: *'The supplier didn't have much experience with equipment of this size.'*
Technology	The process know-how required in the equipment (e.g., principles and basic mechanisms that enable the change in the material processed through the equipment) is new to the supplier firm.	Project G: *"From this point of view, it's a new technology.'*

Managers of high-novelty RMTI projects face additional uncertainty stemming from a lack of full expertise, previous experience and ready, proven solutions within the equipment supplier firms. Technological newness for equipment supplier firms in one or more of the four areas introduces corresponding uncertainties in manufacturing firms' RMTI projects. The findings illustrate corresponding uncertainties introduced in RMTI projects linked with the four types of knowledge gaps on the requirements for development.

Table 11. Technological uncertainties linked to equipment supplier firms' knowledge gaps in four areas

	Uncertainties experienced in the radical manufacturing technology innovation creation process		
Knowledge gap areas	**Front end**	**Development**	**Start-up**
Context-related requirements	- Lack of clarity of the context-related requirements - Lack of clarity of ideas for fitting the technology to the context - Feasibility and performance uncertainties	- Lack of clarity of the context-related requirements and related difficulty in identifying the requirements and accommodating them in the late design phase	- Additional user requirements and/or context requirements are spotted.
Application-related requirements	- Lack of clarity of the application-related requirements - Technology bottlenecks - Feasibility and performance uncertainties	- Lack of clarity of the technological requirements and related difficulties in making the technology work (e.g., trial and error in design)	- Additional technology application requirements are spotted.
Construction-related requirements and performance	- Lack of clarity regarding the details of the full equipment solution - Construction feasibility and performance uncertainty	- Difficulties in designing the details and assembly and in construction (e.g., trial and error, rework)	- The equipment does not work and/or perform as desired. Gaps in construction design need to be resolved.
Technology-related requirements and performance	- Technology feasibility and performance uncertainties	- Difficulties in making the technology work (e.g., trial and error in design)	- The technology in the equipment does not work and/or perform as desired. Gaps in the design need to be resolved.

4.3.2 Contributions of the Article to the Dissertation

Article III contributes a deeper understanding of technological newness for equipment supplier firms and linked uncertainties introduced in manufacturing firms' RMTI creation processes. The in-depth understanding of technological newness for equipment supplier firms offers insights into the management of high technological uncertainty in the different phases of the RMTI creation process. The integrated process view, acknowledging the needed equipment (product) innovation in addition to process innovation as part of an RMTI project, brings attention to an important source of technological uncertainty in addition to technological newness for manufacturing firms.

4.4 Article IV: Managers' Search Practices at the Front End of Radical Manufacturing Technology Innovations

4.4.1 Summary of Findings

Article IV presents the results from multiple-case study on the front end of nine RMTI projects from three firms. The findings illustrate managers' search for three distinct ideas needed for a full RMTI idea and concept: the technology idea, production process idea and equipment idea. Managers were found to engage in the search for these ideas and concepts through directed processes initiated by top management in response to strategic development needs and goals or through autonomous processes carried out by middle managers in response to problems faced in operations. Information was searched internally, within the manufacturing firm, and also externally from equipment supplier firms particularly where needed ideas were not known inside the firm. Figure 4 illustrates the patterns of managers' search practices involving directed and autonomous search modes, and internal and external search spaces. Search and identification of potential equipment supplier firms is also needed, and the practices for these include an open search for the needed supplier firm, in addition to direct discussion with and enquiry from the manufacturing firm's own equipment supplier for needed ideas.

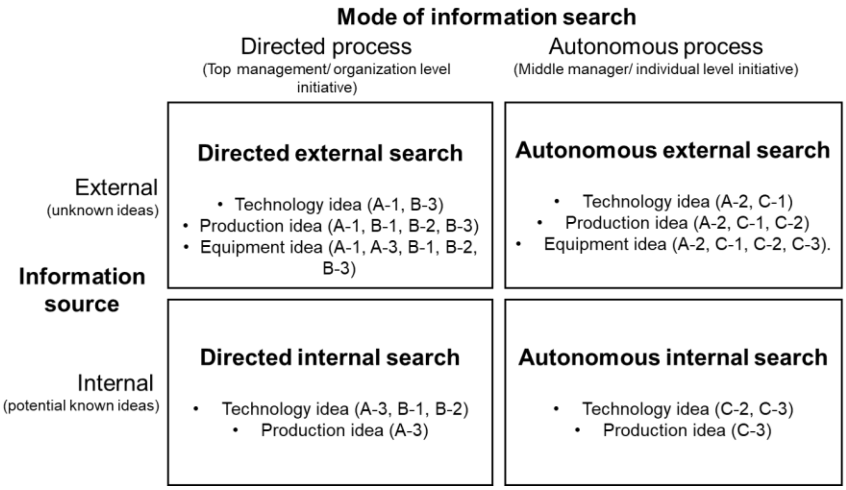

Figure 4. Four patterns of managers' information search practices at the front end of radical manufacturing technology innovation projects

4.4.2 Contributions of the Article to the Dissertation

Article IV contributes a deeper understanding of manufacturing firms' perspective on RMTI creation and managers' information search practices for generating ideas for RMTI. The findings reveal three distinct issues that call for ideas and information searches. This sheds further light on the distinct nature of RMTI ideas and concepts, whose formation involves amalgamation of the process innovation concept for manufacturing firms and the product innovation (equipment solution) concept for equipment supplier firms. Managers play a proactive and important role in the emergence and development of RMTI ideas and concepts.

5 DISCUSSION

5.1 Radical Manufacturing Technology Innovation Creation Processes

The first sub-question for research question 1 was 'What kinds of processes are involved in creating RMTIs with different levels of novelty?' This dissertation presents a framework from manufacturing firms' perspective to understand the types of creation processes for RMTIs with different levels of novelty, with characteristics for categorising RMTIs as having low, medium or high novelty. RMTIs are seen as innovations in the core production processes of manufacturing firms, and the overall RMTI creation process involves the search for and implementation of both process and linked equipment (product) innovations from the perspective of manufacturing firms. The present study extended the previous RMTI creation process models from the perspective of manufacturing firms by covering both equipment (product) and process innovations, whereas the previous research has predominantly covered only the process innovation aspect involved in RMTI creation from the perspective of manufacturing firms (Damanpour & Wischnevsky, 2006; Kurkkio et al., 2011; Lager & Frishammar, 2010; Milewski et al., 2015; Tornatzky & Fleischer, 1990).

The dissertation argues that taking a manufacturing firm–centric view rather than a technology-centric view is advantageous for manufacturing firms' successful management of RMTIs. The innovation front end is a strategic phase in the RMTI creation process from manufacturing firms' perspective, where the RMTI idea and concept emerge. This phase has been insufficiently covered in previous research on RMTIs (Kurkkio et al., 2011; Simms et al., 2021) and requires looking beyond the technology-centric focus linked to technology adoption. Taking a holistic view of the needs and purpose of new technologies in manufacturing is vital for searching for needed solutions as part of managing overall innovation success (Brown, 2001).

Manufacturing firms simultaneously engage in the search for and development of the process and product components of the overall RMTI idea during the front-end phase of idea and concept development and, later, during the innovation implementation phase. This differs from the previous conceptual process models on RMTIs, which suggest a sequential order, from equipment (product) innovation to the manufacturing firm's process innovation, utilising it in its own operations (Damanpour & Wischnevsky, 2006; Lager & Frishammar, 2010). Even though the needed equipment may exist before the start of the innovation process within the manufacturing firm, as part of investigating the RMTI idea and concept at the front end, the manufacturing firm clarifies both the process concept and the needed equipment as part of investigating the RMTI idea. The figure below illustrates the contribution of the present study's findings to previous knowledge on the innovation process for RMTIs.

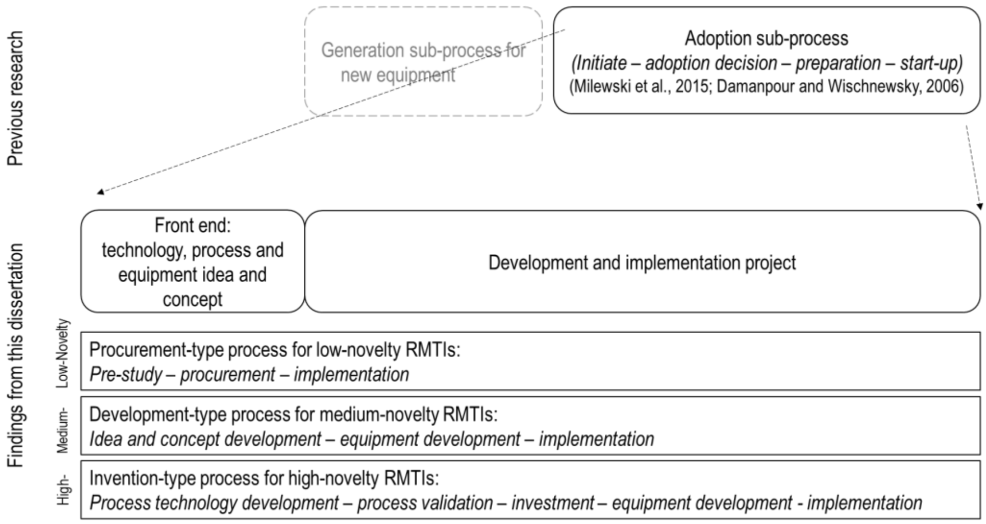

Figure 5. Findings from the present study, extending the previous research on the radical manufacturing technology innovation creation process and the tasks involved from the perspective of manufacturing firms

The above findings extend the previous knowledge on the contingency between the innovation processes and the novelty levels of process innovations (Kurkkio et al., 2011) by illustrating three types of innovation processes for low-, medium- and high-novelty RMTIs (reported in Article II): procurement-type process, development-type process and invention-type process. This extends the understanding of how the creation processes of RMTIs with different levels of novelty differ. The findings suggest that collaborative efforts with equipment supplier firms move more up front in the innovation process as the level of novelty rises in RMTIs. This extends the previous understanding of the collaborative efforts involved with equipment supplier firms during the RMTI creation process (Ahlskog et al., 2017; Linder & Sperber, 2019; Rönnberg-Sjödin et al., 2016; Stock & Tatikonda, 2004) for RMTIs with different levels of novelty.

With the focus on RMTI specifically, the present study's findings emphasise that novelty must be understood in a holistic way to select the right RMTI process; that is, novelty is not only newness for the manufacturing firm but also newness for the equipment supplier firm and for the manufacturer's industry. The findings highlight the impact of technological newness for equipment supplier firms on manufacturing firms' creation process experience. Technological newness for equipment supplier firms introduces linked uncertainties (illustrated in Article III) in manufacturing firms' RMTI creation processes. This is novel compared to previous research on RMTIs and their creation processes, which has mainly considered technological newness for manufacturing firms (Stock & Tatikonda, 2004; Tyre & Hauptman, 1992). It helps characterise the RMTIs that fall in between those introducing new-to-manufacturing firm technologies and those introducing new-to-world technologies and addresses previous calls for a useful categorisation system for RMTIs with different levels of novelty (Reichstein & Salter, 2006).

5.2 Manufacturing Firms' Tasks in Radical Manufacturing Technology Innovation Creation

The second subquestion of the first research question was 'What are the tasks of manufacturing firms in creating RMTIs?' The present study's findings provide a deeper understanding of RMTIs as innovations from the perspective of manufacturing firms. This offers novel insights into manufacturing firms' tasks in RMTI creation as creators, beyond their previously understood tasks in RMTIs as adopters and users of technology developed elsewhere (Ellingsen & Aasland, 2019; Frishammar et al., 2013; Martinsuo & Luomaranta, 2018; Rösiö & Bruch, 2018; Tyre & Hauptman, 1992). Table 12 illustrates the contribution of the present study's findings to previous knowledge on the tasks involved in RMTIs from the perspective of manufacturing firms.

Table 12. Tasks involved in radical manufacturing technology innovation (RMTI) creation from the perspective of manufacturing firms

Innovation process phase	Previous research literature	Findings from this dissertation
Front end	- Pre-study on technology and its implementation, including process and technology development for high-novelty RMTIs - Bringing together the needed stakeholders for systemic innovations - Decision-making, including all-round feasibility evaluation and investment plan	- Information search for needed ideas: technology, process and equipment (including search for potential supplier firms)
Development	- Contributing information on the requirements for equipment development	- Supporting the need for knowledge accumulation by the equipment supplier firm in four knowledge areas: context, application, construction and technology
Implementation	- Start-up of new process - Resolving technical problems in equipment and process - Resolving organisational problems - Training, learning to use the new technology	- Supporting the resolution of technical problems in equipment and technology linked with the knowledge gaps of equipment supplier firms

From the perspective of manufacturing firms, the RMTI front end involves a search for three core ideas involved in it (Article IV): technology idea, process idea and equipment idea. High-novelty RMTI ideas also call for a search for potential equipment supplier firms. Manufacturing firms' (pro)active engagement is important for RMTI idea and concept emergence and development at the front end.

The manufacturing firm's support is needed for the knowledge accumulation needed by the equipment supplier firm, as part of developing equipment solutions that also present technological newness for the equipment supplier firm involved. Manufacturing firms thus need to take a project- rather than firm-level view in planning and managing the knowledge accumulation needs for higher-novelty RMTIs. Knowledge is also accumulated by equipment supplier firms and within the project during the RMTI creation process. This extends the previous discussion on managing knowledge transfer in RMTI projects, which focused mainly on knowledge inflows from equipment supplier firms to manufacturing firms (Linder & Sperber, 2019; Martinsuo & Luomaranta, 2018; Stock & Tatikonda, 2004). The finding on the four-dimensional construct of the knowledge gaps of equipment supplier firms provides a deeper understanding of the kinds of knowledge accumulation needed by equipment supplier firms (Article III): context-, application-

, construction- and technology-related knowledge accumulation. This extends the knowledge from previous studies that focused mainly on production system design and context-related requirements (Bruch & Bellgran, 2012; Rönnberg-Sjödin et al., 2016; Rösiö & Bruch, 2018).

The manufacturing firm's concerns and tasks in the RMTI implementation phase cover the gaps in the knowledge and full understanding of the needed process and equipment (product) innovations. The findings reported in Article III offer a nuanced understanding of the types of challenges and technical difficulties linked with the context- or application-related requirements or the gaps in the construction or technology design. This extends the previous knowledge of the uncertainty experienced during the implementation of a novel technology (Milewski et al., 2015; Von Hippel & Tyre, 1995).

5.3 Information Search Practices of Managers for Radical Manufacturing Technology Innovation Ideas

The second research question was 'How or through what kinds of practices do managers in manufacturing firms search for the information and ideas needed for RMTI at the front end of innovation? The dissertation extends the previous research on managers' practices at the front end of RMTIs (Simms et al., 2021) by revealing managers' search practices for the information needed for developing ideas for RMTIs (Article IV). The locus of the problem, which is strategic at the level of the top managers and operational at the level of the middle managers, influences managers' selection between directed and autonomous modes of information search. The findings illustrate the use of autonomous search practices for RMTIs, extending the previous empirical research that has mainly highlighted the relevance of directed search practices for RMTIs due to the linked investments for the business (Frishammar et al., 2013; Kurkkio et al., 2011). The mapping of managers' use of directed and autonomous search modes for RMTIs is novel because the previous research on search practices for radical innovations has mainly investigated product-related innovations (Reid & de Brentani, 2004; Rice et al., 2001).

Managers in manufacturing firms search for the information needed for RMTI ideas in internal and external search spaces, mainly at equipment supplier firms. Managers seek and engage with information available from internal experts, and an external search is required where there is a lack of required knowledge for the needed technology solutions within the firm. The findings highlight the unique nature of RMTIs compared with the process- or product-only innovation types and the importance of searching for information at both manufacturing and equipment supplier firms as part of the front end. This finding supports the previous research that acknowledges the importance of internal knowledge in manufacturing firms for generating ideas for RMTIs (Linder & Sperber, 2019) and extends the knowledge on the practices of managers in manufacturing firms for bringing together the internal knowledge and the external knowledge from equipment suppliers (Ahlskog et al., 2017).

Manufacturing firms engage in open or closed searches for equipment supplier firms as part of their RMTI idea and concept development. This extends previous empirical research that has mainly illustrated closed search practices for novel equipment ideas among familiar equipment supplier firms (Appleyard, 2003; Terwiesch et al., 2005). The findings bring to attention the lack of known suppliers for high-novelty RMTI ideas and the need for a search for suppliers, in addition to the needed equipment, from manufacturing firms' perspective. An open search for suppliers in the case of RMTI has not been noted before, whereas a wide breadth of external sources for radical idea search has been featured in some studies on radical process innovation (Chiang & Hung, 2010). The present study's findings illustrate the challenge of identifying the supplier–technology dyad as part of radical technology innovations (Melander & Tell, 2014) and highlight its significance in RMTIs.

Managers' proactive search is important in the emergence of RMTI ideas and concepts. The roles of middle managers and their personalities and engagement in conversations with equipment supplier firm experts were important in the discovery of key information needed for some of the cases studied. This is an important area for fostering the emergence of RMTIs, and the present study's findings shed light on this poorly understood aspect of previous research on RMTIs.

6 CONCLUSION

6.1 Theoretical Contributions

The present study's findings have important implications for theory development on the RMTI creation process, as summarised in Figure 6. The findings indicate that, from manufacturing firms' perspective, the RMTI creation process involves both process innovation and bringing in the linked equipment (product) innovation as part of introducing a new technology. The RMTI creation process varies for RMTIs with different levels of novelty. Three types of innovation processes are illustrated for RMTIs with low, medium and high levels of novelty, giving empirical support for the previous findings on the contingency of innovation process on the level of novelty (Kurkkio et al., 2011) and deeper knowledge concerning how the innovation processes vary. This dissertation contributes a comprehensive process model for RMTIs from the perspective of manufacturing firms, complementary to previous studies on process models for RMTI, which have been limited mainly to process concept development (Lim et al., 2006; Kurkkio et al., 2011) and new technology adoption (Damanpour & Wischnevsky, 2006; Milewski et al., 2015; Tornatzky & Fleischer, 1990).

This dissertation argues that RMTIs, as radical innovations in manufacturing firms' core production processes, involve a wider set of tasks for manufacturing firms than simply technology purchase and implementation. Taking a manufacturing firm–centric rather than a technology-centric view of the management of these projects can offer a holistic understanding of their planning and management. This differs from the dominant perspective in the previous research on RMTIs (Ellingsen & Aasland, 2019; Tornatzky & Fleischer, 1990) and offers alternative perspectives to tackle the challenges faced in benefiting from the adoption of new manufacturing technologies (Brown, 2001).

This dissertation contributes to a gap in the previous empirical research on the front end of RMTIs, particularly managers' practices linked with the emergence of RMTI ideas and concepts (Linder & Sperber, 2019; Simms et al., 2021). Managers' proactive search for needed information was found to be important in the emergence and development of RMTI ideas and concepts, extending the previous knowledge on the emergence of RMTI ideas through the practices of managers in manufacturing firms (Ahlskog et al., 2017). The empirical findings on manager's use of autonomous and directed search modes, internal and external information sources and open and closed search spaces involving familiar equipment supplier firms highlight the unique characteristics of RMTIs as amalgamations of process and linked product innovations by equipment supplier firms, against the literature on search practices for product-related radical innovations (Reid & de Brentani, 2004; Rice et al., 2001). A manager's selection from among the alternative search modes and spaces is seen as stemming from the locus at which the need for a new technology is felt, combined with the top and middle managers' relative access to resources and information sources. This contributes to the discussion on managers' selection from among alternative search practices for radical innovation ideas (Bessant et al., 2010; Nicholas et al., 2013) and provides novel insights into managers' selection of search practices specifically for RMTIs (e.g. compared to Kurkkio et al., 2011; Frishammar et al., 2013).

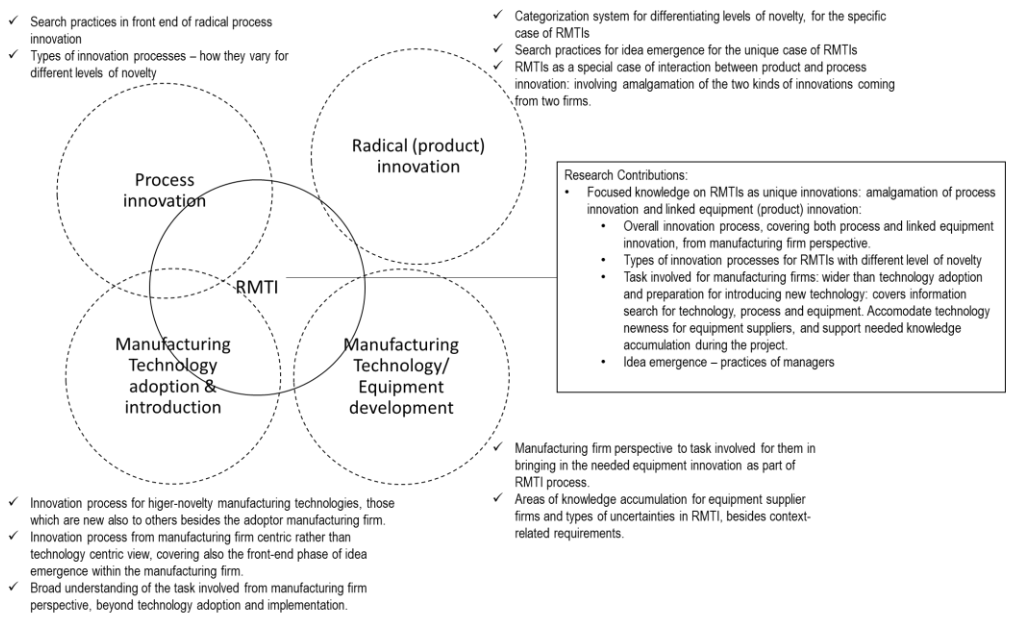

Figure 6. Theoretical contributions of the present study

This dissertation also covers high-novelty RMTIs, helping bridge the gap in previous empirical research on RMTIs. The present study's findings distinguish technological newness for equipment supplier firms as an important characteristic of higher-novelty RMTIs from the perspective of manufacturing firms. This is novel compared with the previous categorisation systems for distinguishing RMTIs based on the overall level of novelty (Lager, 2002; Reichstein & Salter, 2006; Sergeeva, 2016). The study provided further insight into the four dimensions of technological newness for equipment supplier firms and their linked uncertainty experiences in manufacturing firms' RMTI creation processes.

6.2 Managerial Implications

This dissertation encourages taking a comprehensive view of the management of RMTIs as innovations in core production processes and covers the wider set of tasks involved in their management, beyond the purchase and installation of new technology equipment. The dissertation contributes knowledge on innovation processes and managers' practices for the emergence and management of RMTIs from the perspective of manufacturing firms. RMTIs can be distinguished based on whether they introduce novelty mainly for the manufacturing firm or also for the equipment supplier firm and for the industry and the world. The tasks involved are wider in RMTIs with higher levels of novelty, and the creation process varies. The findings regarding the types of processes (Article II) and search practices (Article IV) serve as informative frameworks for firms supporting the planning and management of RMTIs.

This dissertation contributes a close understanding of the nature of RMTIs and the tasks involved in their creation processes from the perspective of manufacturing firms. The RMTI idea and concept comprise three distinct parts: the technology, process concept and equipment concept. Firms may need a comprehensive external search for all parts of the RMTI idea, while at other times some aspects may be well understood internally. The dissertation highlights the importance of proactive search practices for identifying the needed information. RMTI ideas that involve larger investments and concern strategic goals may be initiated through directed investigations at the level of the top managers. RMTI ideas that concern needs and goals at the operations level may be initiated through the autonomous search practices of middle managers. Manufacturing firms play a key role in driving the innovation process across the manufacturing and equipment supplier firms as sponsors or active participants, and at times even play a leading role through the innovation front end, development and start-up phases. Manufacturing firms' tasks in planning and implementing RMTIs span the search, investigation, development and implementation of both the process innovation idea and the equipment (product) idea linked to the implementation of the new manufacturing technology.

Manufacturing firms need to take a project-level view in planning the needed knowledge accumulation. As part of introducing a new-to-firm technology into the manufacturing process, manufacturing firms must accumulate the knowledge and skills needed to use the new technology. For high-novelty RMTIs, the equipment supplier firms' gaps in the knowledge and expertise needed to develop the required equipment (product) part of the RMTI also need to be considered. Thus, the manufacturing firm's tasks are seen as wider than simply managing learning and knowledge accumulation and change within the firm; the manufacturing firm must also support the knowledge accumulation needed by the equipment supplier firm to realise the RMTI.

Manufacturing firms need to pay attention to technological newness for equipment supplier firms as it has an impact on the creation process experience in higher-novelty RMTIs. This factor introduces additional challenges in the form of knowledge gaps and uncertainties in the creation process. The four dimensions of technological newness for equipment supplier firms point to four areas of knowledge and expertise needed by equipment supplier firms as part of RMTI projects: context, application, construction and technology. Thus, context familiarity, which may come from manufacturing firms' close relationships with suppliers, is seen as only one of the four knowledge and experience areas. This suggests the need for careful consideration of the complementarities between partners and identification of suppliers with a project-focused view rather than previous business relationships with the concerned manufacturing firm in the case of RMTIs. Search for potential equipment suppliers, including an open search outside the set of previously known equipment suppliers, is highlighted as an important practice at the innovation front end for identifying the equipment supplier partners needed to realise the required product (equipment) innovation.

Finally, this dissertation brings attention to RMTIs as unique, strategic projects from the perspective of manufacturing firms. The equipment and technology used for the core production method are strategic avenues for radically innovating the firm's production process. The dissertation encourages manufacturing firms to take a manufacturing firm–centric view in managing RMTI projects, with their needs and goals for the innovation at the centre, from idea development to implementation. Technology is part of the solution to manufacturing firms' innovation needs but is not the whole solution. Even though manufacturing technologies are developed in networks with equipment supplier firms, the active participation and support of manufacturing firms are important for new manufacturing technology innovations. By taking a manufacturing firm–centric view, manufacturing firms can influence new technology development to meet their own innovation needs.

Top and middle managers play potentially important roles in the aforementioned matters as they have insights into their technology needs for their manufacturing development. The present study's findings highlight the pathways and practices whereby top and middle managers seek the information needed to generate RMTI ideas. The findings also highlight the importance of their personalities, engagement in conversations and observations that lead to chance events where they come across novel information and lead the initiative at the front end to investigate the idea. The roles and activities of these individuals are important in the emergence of RMTI ideas in manufacturing firms.

6.3 Research Evaluation

The validity of a qualitative research study concerns the accuracy with which the account of the social phenomenon represents the participants' realities (Creswell & Miller, 2000; Maxwell, 1992). A realist approach to validity requires the description, explanation or interpretation of the phenomenon about which the claim is made to be supported by evidence and to address plausible alternative descriptions, explanations or interpretations of the phenomenon. Therefore, the approach to validity is grounded in the concept of a validity threat (a possible way that a conclusion may be wrong) and in ways to address the threat (Maxwell, 1992, 2017; Ronkainen & Wiltshire, 2021).

Three basic kinds of validity (or types of validity threats) relevant to qualitative research are *descriptive* validity, *interpretive* validity and *theoretical* validity (Maxwell, 1992, 2017). These three kinds of validity are based on the levels of understanding that qualitative enquiry aims at, and encompass the perspectives of the researcher, study participants and people external to the study (reviewers, readers), thus seeking to establish the validity of a qualitative study from different viewpoints (Creswell & Miller, 2000). In the following discussion, I use these three types of validity threats as a framework to present the steps taken during this study to foster the validity of the account generated through the study and to discuss the limitations of the work.

Descriptive validity concerns the factual accuracy of an account (Maxwell, 1992, 2017). It is concerned with whether a researcher has invented, mistaken or distorted what they observed (Ronkainen & Wiltshire, 2021). For example, imprecise transcriptions, selective note-taking and faulty memory could be threats to descriptive validity (Maxwell, 2017; Ronkainen & Wiltshire, 2021). Secondary (indirect) descriptive validity concerns the participants' observations of the event, such as how accurately the interviewees recalled what happened during the project in question. Various steps were taken to foster the descriptive validity of the present study. These included collecting 'rich data' during the interviews and recording the interviews on an audio recording device (Coleman, 2021), using an independent professional transcription service, conducting member checking (checking the accuracy of the researcher's understanding of the gathered data with the participants, seeking further clarification from the participants), triangulating data by collecting data from different sources (comparing the data gathered from two or more sources) and maintaining researcher neutrality during data collection. To foster secondary descriptive validity, care was taken in the selection of interviewees by asking the participants to choose a recent example of an RMTI project in which they were closely involved in the exploratory study and by interviewing all the persons closely involved in RMTIs in the case study.

The interviews were conducted in a calm environment, in meeting rooms on the company's premises and were audio-recorded with the permission of the interviewees. The interviewees were given the interview outline ahead of the scheduled interview, and they often came prepared for the discussion, bringing materials to share. The interviewees were allowed to give an uninterrupted account of the RMTI project in which they were involved, and I did not give them many prompts while they were doing this. I was attentive to the accounts being given by the interviewees and later asked many probing questions to capture the full accounts of the innovation processes. Particularly for the case study research, I studied the information gathered immediately after the interviews and returned to the individual interviewees for clarification or to obtain further information where I felt it was needed. In addition, I tried my best to search and gain access to further secondary data sources to improve the richness of the information available on the projects and to triangulate the data.

A main limitation of the exploratory study data was the lack of depth of the data collected per RMTI project. The purpose of the exploratory study was mainly to map a wide breadth of RMTI examples covering different levels of novelty and to gain a broad understanding of their creation processes. Linked with this wide breadth of RMTI examples in the research design, the depth of data collection per project was limited. Care was taken in the data collection by following a thematic interview outline for all projects, building a simple analytical frame for the analyses and excluding projects whose information was deemed insufficient for the data analysis (in Article III, one project was excluded). In contrast to the in-depth case studies in the literature, the exploratory study built upon the informant's first-hand knowledge and sought variety and breadth in empirical examples of RMTIs. Given the previous empirical studies on RMTI that did not cover the full creation process (process and product innovation in RMTI) from the perspective of manufacturing firms, including also high-novelty RMTI examples, such an exploratory study enabled important insights and guided further in-depth research on RMTIs.

Interpretive validity concerns the perspective of the study participants and refers to the accuracy with which the interpretations of the investigated phenomenon reflect the participants' perceptions and experiences (Maxwell, 1992, 2017). I collaborated with the participants to ensure the credibility of the emerging accounts from the study. At the end of the data collection process, I read the interview transcripts, used an open coding approach and prepared a summary of the data and preliminary findings on the central themes for the interviews. I shared the summary and preliminary findings with the participants, providing them with an opportunity for participant feedback. For the case study research, the preliminary findings were discussed with one key coordinator manager within each of the three subject firms. For the exploratory study, the report was shared with all the participants, and a workshop on the preliminary findings was arranged, which was attended by some of the participants.

The case study concentrated on the perspective of managers engaging in idea and concept development; the perspectives of other types of participants, such as engineers, supervisors and participants from outside the firm, were not included.

The studied projects were mainly higher-novelty RMTI projects. The data analysis and conclusions considered these delimitations of the case study design.

Theoretical validity refers to the coherence with which the theories formed explain the events in the real world and the participants' experiences of them (Maxwell, 1992, 2017). It addresses the validity of the theoretical concepts that the researcher brings to or develops during the study and the postulated relationships between the concepts from the perspective of the community concerned with the research (Maxwell, 1992). During the data analysis, I was reflective and conscious of my engagement in interpreting the data and spotting interesting themes and connections in them. I made many iterations during the data analysis to match the emerging inferences with the data; consequently, the emerging inferences went through reorientations, particularly for Articles III and IV. I collaborated and discussed the data and emerging inferences with my thesis supervisor during the data analysis process, which contributed to the rigour of the process of making inferences from the analysis. During the research writing process, my co-author and I followed the good practice of maximising the transparency of the data analysis by using direct quotations from the interviews and giving a detailed account of the analysis to illustrate the process of arriving at inferences from the data. Participation in the peer review process for the individual articles further contributed to the rigour of the data analysis and of the inferences drawn from the data and to their clear presentation in the research articles.

Finally, the present study was limited by its sequential qualitative research design with a critical realist approach, and it was not expected to meet the criteria for research rigour that could be attributed to other research methods and philosophies. It was limited in its scope (e.g. extensiveness of the available data, intensiveness of the data analysis by involving more experts in the analysis process) given its research design and the fact that it was conducted as part of a doctoral research project. These limitations were taken into account when drawing inferences and future research implications from the study.

6.4 Future Research Implications

RMTIs have been predominantly investigated as technology adoption projects from the perspective of manufacturing firms. However, there is more to these projects as radical innovations in manufacturing processes. RMTIs are unique and demanding projects, and there has been limited focused research on them besides the technology adoption and implementation tasks involved from the perspective of manufacturing firms. As a dissertation research project, the present study took a small step within its reach in the direction of a deeper understanding of the creation processes for RMTIs with different levels of novelty from the perspective of manufacturing firms and of managers' search practices for the needed information and ideas at the front end of RMTIs.

RMTIs involve an amalgamation of process innovation and bringing in the linked equipment (product) innovation by the equipment supplier firm, and managers' information search at the front end spans the technology, process and equipment concepts. Thus, the dissertation brings attention to RMTIs as unique radical innovations that present a complex information-processing task for manufacturing firms. While previous research has investigated RMTIs for specific subtasks and within specific phases, further research may investigate the overall innovation process to generate a deeper understanding of the information processing involved from the perspective of manufacturing firms. Further research could also cover the interactions between manufacturing firms' own product innovation processes with their RMTI creation process. The emerging models from this study could be sharpened by also considering the perspective of other actors besides the manufacturing firm, more closely. By exploring more generic ways of characterising RMTIs, broader literature and theories such as turnkey projects, technological learning and absorptive capacity could be drawn upon for enhanced development of theory and tools for supporting the challenges of co-creation environments.

Previous research has also investigated the collaborative efforts involved in RMTIs with equipment supplier firms. This dissertation points at further issues related to the identification of the potential equipment supplier firms needed for developing the RMTI, such as open search, and the need to find the technology–supplier firm dyad that fits the needs of the RMTI development. These issues can be investigated further in future research on RMTIs.

This dissertation points to the part–whole relationship between equipment (product) and process innovations, where the 'product' innovation is important in the full concept and implementation of the process innovation. Previous research has distinguished between product and process innovations and has also explored the links between them occurring within a single organisation. The dissertation adds to this discussion a new circumstance where, as part of process innovation in one firm, there is a need to bring in the needed product innovation from another firm. Future research could further investigate the case of interlinked product and process innovations, taking a holistic view.

The process approach toward innovation in this study has brought attention to *how* firms go about creating these innovations – from their idea to their implementation. Further research could also cover the *impact* side of the innovation involving consequences of RMTIs with different levels of novelty for manufacturing firms.

At the time of writing this dissertation, there is wide engagement in academia and industry in developing novel manufacturing processes to improve environmental sustainability and address other serious problems connected to industrial activity. RMTIs are in a strategic position in the movement towards sustainable manufacturing because many traditional technologies are highly energy-consuming, use non-renewable raw materials and generate environmental pollutants. Future research on sustainable manufacturing technology development could step beyond the technology-centric view (understanding and supporting technology development, diffusion and adoption) and also take into account the innovation processes within manufacturing firms with a manufacturing firm–centric view to highlight the potential of manufacturing firms for innovating their core processes and creating novel technology solutions for their production. This will also broaden RMTI research's narrow focus on the implementation of a few select advanced technologies to create the knowledge and understanding needed by manufacturing firms to innovate their tools and technologies.

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I

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Successful Creation of Radical Manufacturing Technology Innovations

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Abstract Manufacturing technologies are often developed incrementally, and less attention has been directed at radical innovations. Radical manufacturing technology innovations pursue significant performance improvements in the production process and are expected to enhance the competitiveness of the firm. This paper explores the successful creation of radical manufacturing technology innovations by analyzing previous empirical research and characterizing the emergence and management of the innovations. Companies engage in radical manufacturing technology innovations by bringing in advanced manufacturing technologies, carrying out technology-related R&D in processes, and innovation in their supply chain processes. Innovation by adopting new technologies developed elsewhere appears as more dominant than innovation by creation. Forthcoming research is proposed on different management practices for different types and contexts of manufacturing technology innovations, and on how digitalization-related innovations can be made into a source of competitive advantage.

Keywords: manufacturing technology, radical innovation, success

1 Introduction

Radical innovations in products and technologies have a high impact in terms of offering completely new benefits, significant improvement in known benefits, or significant reduction in costs (O'Connor et al. 2006, Maine et al. 2014). As such, radical innovations have a significant potential to increase the competitive-

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ness of a firm in its industry. During the past three decades competitive pressures on manufacturing firms in advanced industrial economies have increased because of various reasons such as globalization, economic crises and the rise of manufacturing strongholds in emerging economies (MacBryde et al. 2013). The importance of creating successful radical innovations in manufacturing firms has therefore increased.

However, there is another side to the development of radical innovations, namely the high risk and uncertainty associated with them. Previous research has suggested that some radical innovations can only be developed through spin-offs or entrepreneurial ventures, outside of the incumbent firms (e.g. Christensen 1997). Also, research suggests that mature technology firms have great difficulties in repeated innovations (Dougherty & Hardy 1996). In order to survive under competitive pressures, companies are required to rejuvenate their manufacturing systems, which will require both incremental and radical innovations in manufacturing technologies. Whilst continuous, incremental innovations are built into the routines of manufacturing firms (Klingenberg et al. 2013), much less attention has been directed at radical manufacturing technology innovations. Therefore, the success of radical manufacturing technology innovations presents a relevant and important research gap.

The purpose of this paper is to explore the successful creation of radical manufacturing technology innovations. The goal is increased understanding on the sources, characteristics and success factors in creating radical innovations in manufacturing, and the identification of research gaps to guide further research. The focus is on two research questions:

1. How do radical innovations in manufacturing technologies emerge?
2. How are successful radical innovations in manufacturing technologies managed?

This paper will synthesize evidence from existing empirical studies on radical innovations in manufacturing technologies. Previous empirical research on radical manufacturing technology innovations were sought from the key journals of operations and innovation management. This involved a preliminary keywords based search in ISI (Web of Knowledge) database using *radical innovation in manufacturing technology* which resulted in 71 articles. These were used as a starting point for locating relevant articles, journals and authors, and guided further efforts in locating empirical research-based journal publications discussing emergence and/or management of radical innovations in manufacturing technology. The articles were reviewed taking a content analytical approach, to identify common themes and differences. The analysis results in a summary of what has been studied and is known already and identification of gaps in knowledge to guide further empirical work in the field.

2 Success of Radical Innovations in Manufacturing Technologies

An innovation is an entrepreneurial endeavour to introduce a change in the commercial and industry environment (Drucker, 1985; Schumpeter, 1934). Schumpeter defined an innovation from an economic perspective as the introduction of a new good – or of a new quality of a good, the introduction of a new method of production, the opening of a new market, the conquest of a new source of raw/ semi-processed material, or carrying out the new organization of any industry (Schumpeter 1934, p. 66). In this research, we consider primarily the innovations concerning the introduction of a new production process.

Based on the degree of novelty in the technology and configuration involved in innovations, they may be categorized as radical or incremental. Radical innovations involve distinct new knowledge or (re-)combination of existing knowledge, whereas incremental innovations take minor steps and involve little novelty (Raymond and St.Pierre 2010). Innovation radicalness is easier to sense than to define or measure (Dewar and Dutton 1986) and can be represented on a continuum between radical and incremental as the endpoints (Buschgens et al. 2013). Discrepancies over what constitutes 'radicalness' also arise from whether the level of newness can be defined at the level of the firm (e.g. Damanpour et al. 2006), at the level of the industry (e.g. Sinha and Noble 2008) or at the level of technology that is new-to-the-world (e.g. Chang et al. 2012). In this paper, we review studies on radical manufacturing technology innovations without giving regard to the discrepancies in how radicalness is defined. We refer to the core production technology involved within the overall new production process as radical manufacturing technology innovation (RMTI).

Existing research on RMTI can be broadly divided into three primary themes: 1. adoption and integration of AMT (advanced manufacturing technology) within firms, 2. technology-driven process R&D (research and development), and 3. supply chain process innovations.

1. The advent of computerization that started around 1970s in the traditional mechanized and manual production equipment has been one of the major changes in the history of manufacturing, and has contributed to large number of RMTIs commonly referred to as Advanced Manufacturing Technologies (Khazanchi et al. 2007). Pennings (1987; See Gomez and Vargas 2012) defined AMT as "an automated production system of people, machines and tools for the planning and control of production processes, including the procurement of raw materials, parts and components and the shipment and service of finished products". Typical examples of AMT include computer numerical controlled machines, computer aided design, robotics and flexible manufacturing systems, and these technologies share a typical characteristic that they are easy to inte-

grate electronically (Gomez and Vargas 2012). Some research studies include manufacturing planning systems, such as Just-in-time, Manufacturing Resource Planning and Enterprise Resource Planning under the umbrella term AMT (Swink and Nair 2007).

2. Research on technology-driven process R&D focuses on the science-based and technical development of new methods of production. These are often difficult to distinguish from within overall R&D activities, where radical product and process innovations are intertwined (Raymond and St.Pierre 2010). New-to-the-world innovations involve multiple technical breakthroughs and RMTI lie at the link between a successful invention and its commercialization. An example of ongoing process R&D could be reducing the production cost of fuel cells, which is currently a major issue withholding their commercialization (Kawase 2015).
3. Research on supply chain process innovations is often focused at the firm level. It encompasses both developments in the manufacturing methods by use of new equipment and improvements in the organization and coordination of various production and distribution activities. Supply chain process innovations may or may not involve the use of new technology, and accordingly can be divided into technological and organizational types (Reichstein and Salter 2006). Research on radical technological process innovations in firms shows that adoption of RMTI is a major source of radical supply chain process innovations in manufacturing firms (e.g. Reichstein and Salter 2006; Hervas-Oliver et al. 2014).

The success of a RMTI lies in the realization of the radical performance improvement in the output produced by utilizing the new production process. For example, Gomez and Vargas (2012) and Cardoso et al. (2012) perceive that the success in adoption of new technology in production lies in the effective functioning of the overall new production process and the resulting 'utilization' of the new technology to improve the overall performance of the production output. Various measures of success have been used in earlier research. Swink and Nair (2007) measure success using five dimensions of manufacturing performance: cost efficiency, quality, delivery, process flexibility, and new product flexibility. Hervas-Oliver et al. (2014) measure success in manufacturing innovation based on improvement in three production process indicators of cost reduction, flexibility and capacity improvement. Khazanchi et al. (2007) measure success of manufacturing innovation based on plant-level performance areas of product quality, scrap minimization, on-time delivery, equipment utilization and manufacturing lead time by using subjective scales of measurement. The reviewed literature also involved use of objective firm-level measures of success in RMTI such as sales growth (Dewar and Dutton 1986) and firm survival (Sinha and Noble 2008). Therefore, measurement of success in RMTI relies on the overall performance improvement in the output made by the new production process.

3 Emergence of Radical Innovations in Manufacturing Technologies

At a given point in time, a production technology in use must submit to commercial appropriateness (Schumpeter 1934), or as Schumpeter put it, the half-artistic joy of technically perfecting the productive apparatus is disregarded in business. Research and development for the creation of radically new production methods is as important as its successful adoption and utilization within the existing production process or its implementation within a completely new production process.

Existing research on RMTI suggests that the development and utilization of RMTI occur in different organizations. Damanpour and Wischnevsky (2006) distinguish between innovation generation and innovation adoption, and according to their research, the processes of generating and adopting innovations are distinct phenomena that are facilitated in different organizational conditions. Organizations that innovate-by-generation and those that innovate-by-adoption differ with respect to their innovation capabilities, processes and culture. They emphasize that the emergence of RMTI within firms that innovate-by-generation and innovate-by-adoption follows different paths. The phases of innovation generation include: recognition of opportunity, research, design, commercial development and marketing; whereas the innovation-by-adoption includes two main phases: initiation and implementation. (Damanpour and Wischnevsky 2006)

Table 1 summarizes existing studies on the emergence of RMTI in firms. Many of the research results highlight the role of the organizational context. The observed set of studies focus dominantly on RMTI-by-adoption, and few studies consider RMTI-by-generation (Raymond and St.Pierre 2010, Reichstein and Salter 2006, Un and Asakawa 2015).

Acquisition and utilization of new machinery and equipment is one of the major modes of RMTI in firms (Reichstein and Salter 2006, Hervas-Oliver et al. 2014, Khazanchi et al. 2007, Ettlie et al. 1984). Review of previous empirical research on innovation-by-adoption (See Damanpour and Wischnevsky 2006) reveals that the initiation phase consists of recognizing a need, becoming aware of a possible innovation, and evaluating its appropriateness, leading to the decision to adopt the innovation. The implementation phase consists of all events and actions that pertain to modifying the innovation and the adopting organization, using the innovation initially, and continuing to use the innovation until it becomes a routine feature of the organization. Therefore, organizations form the context for the adoption and utilization of RMTI.

Table 1 Empirical studies on the emergence on radical manufacturing technology innovations.

Source	Context	Methodology	Key finding for this study
Ettlie et al. (1984)	Adoption/ creation of new packaging RMTI for cooked and sterilized food in meat, canning and fish industries in USA	Statistical analyses; Data collection by survey (n=147) and interviews (n=56)	Aggressive technology policy and concentration of technical specialists promote RMTI
Dewar and Dutton (1986)	Adoption of RMT in footwear manufacturing firms in USA.	Statistical analyses of survey data (n=40)	Size and depth of knowledge resources are significant predictors of adoption of RMTI
Gomez and Vargas (2012)	Adoption of AMT (numerically controlled machines, robotics, computer aided design, flexible manufacturing) in Spanish manufacturing firms	Statistical analyses of secondary data from annual surveys in 1994, 1998, 2002, 2006	Complementary assets, such as technological resources (R&D), are important determinants of RMTI
Raymond and St. Pierre (2010)	Product R&D, process R&D and their associated innovation outcomes in 205 Canadian manufacturing SMEs	Statistical analyses of secondary data from survey	Link between product R&D intensity, process R&D intensity and innovation outcomes in firms is governed by contingencies.
Reichstein and Salter (2006)	Process innovations in 2881 manufacturing firms in UK in 2001	Statistical analyses of secondary data from survey	Major determinants of RMTI in firms include presence of radical product innovations, firm strategies focusing on cost-leadership or product development and active collaboration with equipment suppliers.
Un and Asakawa (2015)	Process R&D collaboration partners of 781 manufacturing firms in Spain between 1998-2002	Statistical analyses of secondary data from survey	Suppliers and universities form potential process R&D collaborators, against customers or competitors.

According to existing research on the emergence of RMTI within firms, the strategy and structure of organizations determine the propensity for a firm to engage in the creation or adoption of RMTI (Ettlie et al. 1984). Ettlie et al. suggest that an aggressive technology policy and unique structural arrangements, such as concentration of technical specialists, centralization and informal structures, result in favourable pre-innovation conditions supporting radical process adoption.

While evidence in empirical research supporting unique structures such as centralization of authority as predictors of RMTI in firms remains weak (e.g. Dewar and Dutton 1986), generally consistent results have been observed regarding technological resources at firms in determining the likelihood of RMTI (e.g. Dewar and Dutton 1986, Gomez and Varga 2012, Raymond et al. 2010, Reichstein and Salter 2006).

Earlier studies have attempted to establish causal links between some firm level characteristics and the likelihood of emergence of RMTI in firms. For example, Gomez and Varga observed that firm size, propensity to export and being part of business group act as predictors of the likelihood of RMTI. Reichstein and Salter (2006) observe that firm size and close relation with suppliers are predictors of process innovations in firms. Un and Asakawa (2015) suggest close collaborations with suppliers and universities to be sources of RMTI for manufacturers. In the case of the adoption of AMTs, previous experience in the use of AMTs at a firm acts as significant predictor of RMTI involving AMTs in future. Since AMTs can be integrated electronically, existence of AMTs within a plant encourages adoption of other technologies that can be integrated with the existing AMTs to obtain systemic benefits of AMT (Da Rosa Cardoso et al. 2012; Sinha and Noble 2008).

4 Managing Radical Innovations in Manufacturing Technologies

Managing RMTI appears as somewhat different, depending on the approaches and sources of the innovation. According to Damanpour and Wischnevsky (2006), in the case of innovation-by-creation, the critical innovation issue is to manage the innovation project in a timely and efficient fashion, whereas in the case of innovation-by-adoption, it is to assimilate the technology extensively into the organization in order to produce the desired organizational change. They perceive that the key managerial challenge in the generation of innovation is matching of the organization's technical capabilities with market opportunities; whereas the key managerial challenge in innovation-adopting organization is matching the organization's strategic requirement with capabilities and potentials of the innovations existing in the market. Despite the expected potential of RMTIs to result in radically improved production performance measures, for example in the case of AMT, only 25-50% of the implementations are observed to be successful in achieving the projected improvements (Khazanchi et al. 2007).

Table 2 summarizes previous research on key issues in managing RMTIs successfully. Five main topics emerge from previous research as key factors: 1) a supportive organizational culture and control; 2) external integration; 3) internal integration; 4) efficient use of complementary assets; and 5) timing of the RMTI.

Table 2 Empirical studies on the successful management of radical manufacturing technology innovations.

Source	Context	Methodology	Key finding for this study
Buschgens et al. (2013)	Previous studies on relation between organizational culture and innovation	Meta-analytic review	Positive correlation between successful innovations and presence of a developmental culture, based on values of flexibility and external orientation; negative correlation with presence of a hierarchical culture
Da Rosa Cardoso et al. (2012)	Implementation of new production technologies in firms in Brazil.	Mixed-method analysis of qualitative data (literature review, secondary data, expert/ practitioner interviews)	Organizational design, mainly structure, needs to be reviewed as part of decision to adopt particular AMT.
Swink and Nair (2007)	AMT adoption in manufacturing plants in North America.	Statistical analysis of survey data	Design-manufacturing integration acts as complementary asset, supporting in realizing maximum benefits of AMTs.
Khazanchi et al. (2007)	Adoption of similar AMT (computerized die/ mold machinery) in a large sample of firms in North America.	Statistical analyses of survey data.	Flexibility values in a firm's culture are critical for success in AMT implementation.
Stock and Tatikonda (2008)	Adoption of wide category of technologies (operational and non-operations uses) in a large-sample (91 firms) of firms in USA.	Statistical analyses of survey data.	Highlight the importance of inter-organizational factors (between firm and technology supplier) in success in new technology implementation.
Sinha and Noble (2008)	New manufacturing technology adoption in UK's metal working and engineering industry in 1981 and 1986	Statistical analyses of survey data.	Proper timing of adoption decisions in firms related to new production technology are critical in determining firm survival.

Organizational culture and control. Research on the successful management of RMTI addresses the challenge of managing the team members involved in radical innovation projects because such work is difficult to measure and control in terms of both behaviour and output (Buschgens et al. 2013). Buschgens et al.'s research suggests that the best way to control progress of radical innovation projects is through organizational culture and alignment of individual's objectives with the firm. Management of innovation requires paradoxical enablers in an organization's culture. On one hand, it requires a culture of flexibility and empowerment, to enable creativity, empowerment and change that drive exploration necessary for radical innovations, and on the other hand control and efficiency in order to drive delivery of results with discipline and focus on outcomes (Khazanchi et al. 2007). In the case of implementation of AMT in manufacturing plants, Khazanchi et al.'s research suggests that the combination of flexibility and control values in organizational culture, congruence in perception of values between managers and operators have a positive influence on the plant performance outcome when adopting RMTI.

External integration. Some studies focus on the interaction between the technology supplier and the innovation adopter firm as a key ingredient in managing the RMTI successfully. In particular, Stock and Tatikonda's (2008) research recommends increased user involvement in RMTI development for greater implementation success. They observed a positive relation between higher project criticality, i.e. more attention and resources and successful management of innovations involving external technology adoption. Advanced processes and supplier integration are needed for manufacturing firms to manage external technology adoption in their production successfully (Stock and Tatikonda, 2008).

Internal integration. The success of a new manufacturing technology adopted in a firm's production process comes from its successful integration into other organizational elements (Hervas-Oliver et al. 2014, Khazanchi et al. 2007). Technology is only an enabler, whereas the architecture in which it is placed has a far greater impact in the firm's success (Gomez and Vargas, 2012). Previous research has revealed various enablers for integrating new technologies into a firm's own processes. For example, a preceding analysis of the impact of manufacturing technology adoption and implementation on the organizational characteristics is recommended as a part of the manufacturing technology selection process (Da Rosa Cardoso et al. 2012; Stock and Tatikonda 2008). Also, the firm must plan reviewing its existing organizational characteristics in order to prepare for the change process and set realistic expectations (Stock and Tatikonda 2008, Da Rosa Cardoso et al. 2012). They should also establish a coordination group to manage the process of the manufacturing technology selection, adoption and implementation (Da Rosa Cardoso et al. 2012). Finally, communication of intended improvements through technological change could mobilize resources and personnel better (Da Rosa Cardoso et al. 2012).

Efficient use of complementary assets. Complementary assets are resources or capabilities that allow organizations to capture the profits associated with a strategy, technology or innovation (Teece 1986; See Swink and Nair 2007). These assets may be tangible, such as existing equipment (Sinha and Noble 2008) or intangible, such as R&D investments (Gomez and Vargas 2012). Swink and Nair (2007) suggest design-manufacturing integration as an important complementary asset for RMTI involving the adoption of manufacturing technology. An effective process of combining product and process specialists can contribute to generating appropriability from the RMTI. This can also contribute toward better planning of the RMTI adoption by considering links to the firm's overall manufacturing strategy, since there are possible trade-offs between various technology-performance relationships. Some of the other examined contingencies for the success of RMTIs are infrastructural and demographic variables such as worker empowerment, quality programs and process type (Swink and Nair 2007).

Timing of RMTI. Given the time-sensitive nature of returns on investment in certain manufacturing technologies, success of RMTI also depends on capability of firms to make timely decisions about their adoption (Sinha and Noble 2008, Agkun et al. 2014). This capability is related to presence of typical characteristics in organizational culture, notably the willingness to cannibalize, values for future orientation and tolerance are also important for enabling success with radical innovations (Buschgens et al 2013).

Besides the management of successful RMTIs, enablers of success in RMTI have been analysed from various perspectives. In their review, Damanpour and Wischnevsky (2006) observe the following as enablers of success in innovation-by-creation: business-project fit, R&D-manufacturing-marketing-interaction, the uniqueness of the innovation, the user-benefit or economic advantage of the innovation, the role of an innovation champion, patent protection and competition in market, among others. On the other hand, they review that the factors that predict successful innovation-by-adoption include organizational complexity, centralization of decision making, organizational members' internal and external communication, perceived risk of the innovation, the capacity of the organization to absorb information, and the complexity of the innovation.

5 Discussion and Conclusions

We have investigated the emergence of radical innovations in manufacturing technologies through reviewing earlier empirical research in technology-related operations and innovations. Earlier research has had a strong emphasis in the adoption of advanced manufacturing technologies (e.g. Khazanchi et al. 2007, Gomez and Vargas 2012) and it has covered also technology-based process R&D (Raymond and St.Pierre 2010) and supply chain process innovations (Reichstein and Salter 2006). The dominant view emphasizes manufacturing firms as adopters of RMTI developed elsewhere, instead of creators of RMTI. As technology suppliers can provide RMTI to multiple firms, the real innovation is not in its adoption, but in how well firms master their utilization as a source of competitive edge. Many studies reviewed in this paper focused on how to manage the successful adoption of technologies, and not so much on how to manage their creation and utilization.

A particular interest was to understand how successful radical manufacturing technology innovations are managed. Success is covered in previous research in terms of the performance improvement of the production process, and it has been assessed through quite ordinary measures of costs, quality, flexibility, delivery efficiency and capacity (e.g. Swink and Nair 2007, Hervas-Oliver et al. 2014). Our review showed that the successful management of RMTI requires a supportive organizational culture and control; integration of external suppliers; internal integration; efficient use of complementary assets; and the right timing of the RMTI.

The results show tentative indications that different kinds of enablers and management practices are needed for different types of manufacturing technology innovations, and in the different phases of creating, adopting and utilizing them. As radical manufacturing technology innovations have been studied merely from some parts of these viewpoints and with certain types of technologies, more research is needed on the contingent nature of managing RMTIs.

Currently digitalization (e.g. sensors and remote monitoring, internet of things, 3D printing) is changing the nature of production in existing industries. As there is hardly any focused research on these RMTIs, comparable with AMT, digitalization-related manufacturing innovations are proposed as an important avenue for future research. Even if digitalization can be considered a generic innovation that can potentially affect any manufacturing firms, its radical potentials for specific firms and networks and for the industry more generally call for further research. Particularly the institutional implications of digitalization to the manufacturing industries deserve further research attention.

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Creation Processes for Radical Manufacturing Technology Innovations

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Creation processes for radical manufacturing technology innovations

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Abstract

Purpose – This paper empirically investigates the processes by which manufacturing firms create radical innovations in their core production process, referred to as radical manufacturing technology innovations (RMTI). The purpose of this paper is to improve the understanding of the processes and practices manufacturing firms use to create RMTI.

Design/methodology/approach – Creation processes for 23 RMTI projects from diverse industry and technology contexts are explored. Data were collected via semi-structured interviews, and an inductive analysis was carried out to identify similarities and differences in RMTI types and creation processes.

Findings – Three types of RMTI and three alternative RMTI creation processes are revealed and characterized. An integrated view is developed of the activities of the equipment supplier and the manufacturing firm, highlighting their different roles and interaction across the three RMTI creation process types.

Research limitations/implications – The exploratory design limits the depth of the analysis per RMTI project, and the focus is on manufacturing technology innovations in one country. The results extend previous case and context-specific findings on RMTI creation processes and provide novel frameworks for cross-case comparisons.

Practical implications – The manufacturing firms' proactive role in RMTI creation is defined. A framework is proposed for using different RMTI creation processes for different types of RMTI.

Originality/value – This study addresses recent calls for empirical research on understanding the ways in which process innovations unfold in manufacturing firms. The findings emphasize the role of manufacturing firms as creators of RMTI in addition to their role as innovation adopters and implementers and reveal the suitability of different RMTI creation processes for different RMTI types.

Keywords Technological innovation, Radical process innovation, Manufacturing technology, Creation processes in firms

Paper type Research paper

1. Introduction

The development of production operations can occur through incremental, continuous improvements, or through radical shifts in the method of production. This study focuses on the latter, i.e., the development of production through a radical shift in the core production technology and process, here labeled as radical manufacturing technology innovations (RMTIs). In practice, this implies the introduction of new industrial equipment (Reichstein and Salter, 2006; Milewski *et al.*, 2015) that embodies a new method of production, and may involve the invention, development and piloting of new technological and process know-how in the core production operations of the firm.

Previous studies on new industrial equipment dominantly cover the implementation of RMTIs as new technology development and technology transfer from the perspective of the industrial equipment supplier firms (e.g. Stock and Tatikonda, 2008; More, 1986;

Von Hippel, 1978). Various RMTIs have been covered in different contexts, including: new technology innovations in footwear manufacture such as flow molding, numerically controlled stitchers and computer pattern generating systems (Dewar and Dutton, 1986); new packaging technologies for cooked and sterilized food (Ettlie *et al.*, 1984); and various forms of automated manufacturing technologies such as numerically controlled machines and robotics (Gomez and Vargas, 2012; Khazanchi *et al.*, 2007). With the supplier-centric focus, some studies have indicated that it is crucial for the equipment suppliers to understand the perspective of the customers, lead users in particular, for them to be able to implement the innovations successfully on the market (Baldwin *et al.*, 2006; Von Hippel, 1978).

Indeed, particularly in the implementation of RMTI, it is necessary to understand the technology-adopting manufacturing firm's perspective. Even if the novel process and technology were well-established in the manufacturing firm's industry, they may be new for the adopting manufacturing firm. Previous research shows that the implementation of RMTIs presents many unknowns and challenges, dealing with the modification and adaptation of a component technology, the equipment and the entire process to fit the needs of the specific manufacturing firm (e.g. Milewski *et al.*, 2015; Tyre and Orlikowski, 1994; Leonard-Barton, 1988; Von Hippel and Tyre, 1995).

Compared to RMTI implementation and adoption, few studies have investigated the ideation and development (or creation) of RMTI, and there is a dearth of empirical research on this topic (Lager and Frishammar, 2010; Kurkkio *et al.*, 2011). The few studies that do exist are mainly single or multiple case studies limited to specific industries, most of them concentrating on process-based industries (e.g. Lim *et al.*, 2006; Linton and Walsh, 2008; Lager *et al.*, 2010; Frishammar *et al.*, 2013). This creates a need for further evidence on RMTI processes from diverse contexts, to address the different requirements in different industries (Linton and Walsh, 2008; Lager and Frishammar, 2010; Kurkkio *et al.*, 2011; Rönnberg-Sjödin, 2013), and in technologies at different maturity levels (Lim *et al.*, 2006).

The purpose of this research is to improve the understanding of the processes and practices manufacturing firms use to create radical innovations in their core production processes. The research seeks answers to two main questions:

RQ1. What types of processes do manufacturing firms use to develop RMTIs?

RQ2. How do these processes vary across different RMTI projects?

The focus is on the perspective of the manufacturing firm radically innovating its production process, but the perspective of equipment supplier firms is considered as well, since novel production technology and equipment are created in and between the manufacturing firm and the equipment supplier firm (Frishammar *et al.*, 2013; Baldwin *et al.*, 2006; More, 1986).

The focus is on the core production process of the manufacturing firms, and we do not cover innovations in enabling processes (as included in Milewski *et al.*, 2015) or incremental process innovations (as included in Kurkkio *et al.*, 2011). We explore the creation processes of 23 RMTI projects from different contexts (industries, technologies and firm sizes), to determine their similarities and differences. The research offers evidence regarding alternative types of RMTI and different RMTI creation processes. The findings reveal manufacturing firms' use of certain RMTI process types for specific types of innovation novelty, and the activities of equipment suppliers and manufacturing firms during the RMTI processes. In doing so, RMTI are characterized through a wide variety of recent industrial examples, answering to a challenge described in previous studies (e.g. Reichstein and Salter, 2006) on how to define and sort radical innovations from other process innovations.

The following Section 2 reviews previous research on RMTI creation processes. Section 3 describes the research design, data collection and analysis method. Section 4 presents the findings on RMTI types, processes and activities in the 23 RMTI projects, and Section 5 further discusses the findings. Section 6 concludes the contributions, limitations and implications for practice and further research.

2. Literature review

Section 2.1 introduces the terminologies and conceptualizations of radical technology and process innovations based on previous research, and positions the concept of RMTI among other types of innovations. Section 2.2 discusses the meaning of "radical," differentiating it depending on the novelty of the innovation. It also builds a foundation for understanding differences between RMTI projects. Section 2.3 summarizes the present understanding on RMTI creation processes, manufacturing firm's and equipment supplier firms' activities in them, and the need to investigate RMTI creation processes across different projects.

2.1 Radical manufacturing technology innovations: definition and positioning

Radical technological innovations involve the introduction of a technology that is radically novel and different from the previous technology it may be displacing. For example, fuel cell technology that is expected to replace traditional engines in automotive industry can be considered a radical technological innovation (Harborne *et al.*, 2007). While such product-related technological innovations may offer direct benefits to end-users, manufacturing companies seek technological innovations also in their own processes, to achieve higher performance in terms of value, efficiency and quality. In the present study, we take the perspective of manufacturing firms radically innovating their core production process, as there is a call for further research regarding process innovations (Lager and Frishammar, 2010; Kurkkio *et al.*, 2011).

In this study, we focus on RMTIs that transform the manufacturing firm's core production processes used to directly shape and make the products. RMTIs do not deal with peripheral or enabling processes in manufacturing plants such as those used for production quality control and monitoring (Bessant, 1982), innovations in other than manufacturing operations such as material purchase processes (Parikh and Joshi, 2005), or other types of process innovations such as those concerning commercial issues. Where process innovations in general can cover any types of processes (core, non-core production processes, material, financial and information flows, commercial processes, administrative processes, etc.) and any types of innovations (radical, incremental, material and immaterial, technological and non-technological, organizational, administrative and managerial, etc.) (Milewski *et al.*, 2015; Reichstein and Salter, 2006), this study is focused on RMTI only. Figure 1 shows the distinction between RMTI and other technological process innovations in manufacturing.

Previous research in the field of technology management has covered some issues related to RMTI such as new technology adoption (Raymond and St-Pierre, 2005; Sinha and Noble, 2008; Gomez and Vargas, 2012; Akgun *et al.*, 2014), implementation of new technologies in production (Khazanchi *et al.*, 2007; Swink and Nair, 2007; Stock and Tatikonda, 2008; Karlsson *et al.*, 2010; Da Rosa Cardoso *et al.*, 2012), technology and knowledge transfer (Frishammar *et al.*, 2015; Datta and Jessup, 2013; Lee *et al.*, 2010) and technology diffusion (Antonelli, 2006). In these studies, the manufacturing firm is dominantly perceived as an adopter, buyer and user of a technology developed elsewhere, whereas the development of the technology is not in focus. As our interest is both in the creation of RMTI and its implementation, it is not sufficient to cover the technology adoption perspective only.

	Radical innovation	Incremental innovation
Core manufacturing process	Radical manufacturing technology innovations (RMTI) - New production method for the manufacturing process - Implies the use of novel technology equipment ▪ e.g. new technology innovations in footwear manufacture such as flow molding, numerically controlled stitchers and computer pattern generating systems (Dewar and Dutton, 1986)	Incremental manufacturing technology innovations - Same production method, but slightly enhanced, modified or improved, e.g. to improve efficiency or quality • e.g. enhanced technology equipment in footwear manufacture with automatic needle positioner and thread trimming (Dewar and Dutton, 1986)
Enabling processes in the manufacturing plant	Radical technological innovations in enabling processes - New process, not directly concerning the core production but enabling or supporting it - Implies use of novel technology • e.g. Implementation of RFID technology for component flow monitoring (Zelbst *et al.*, 2012)	Incremental technological innovations in enabling processes - Same process, but slightly enhanced, modified or improved, e.g. to improve efficiency or quality • e.g. Better ERP system (Barth and Koch, 2019)

Figure 1.
Technology innovations in manufacturing, and the positioning of RMTI

Research on the development of new industrial equipment covers the ideation and development processes of RMTI, from the perspective of a technology supplier. Some of such studies acknowledge the involvement of the customers, e.g., in terms of open innovation (Sjodin *et al.*, 2011; West and Bogers, 2014), co-development (Appleyard, 2003), joint R&D (Frishammar *et al.*, 2015) and other ways of collaboration (Terwiesch *et al.*, 2005; Hausman and Stock, 2003; Dulluri and Raghavan, 2008; Von Hippel, 1978; More, 1986). However, these studies dominantly concern the empirical contexts of equipment supplier firms, and their focus is on how the equipment suppliers can develop and sell their technologies successfully and facilitate their use in technology-adopting manufacturing firms (Frambach and Schillewaert, 2002; Ng *et al.*, 2013; Baptista, 2013). Such studies are limited as they do not inform the perspective of manufacturing firms in creating the radical technological innovation within their core process.

While manufacturing firms' technology adoption and equipment supplier firms' equipment development processes are relevant and informative for this study, they appear as disconnected and do not offer a comprehensive view on RMTI creation processes from the perspective of manufacturing firms. Since "adoption and innovation are two complementary aspects of a broader process involving the introduction of localized technological changes that build upon the creative adoption and recombination of internal and external technological knowledge" (Antonelli, 2006), there is a need to consider the creation of RMTI more comprehensively for the manufacturing firms. As the manufacturing firm and its suppliers face the novel manufacturing technologies from their unique circumstances, there is a need to delve deeper into what is "novel" and "radical" in their specific context.

2.2 *Radical manufacturing technology innovations: degrees and types of novelty*

The term "radical" is used to refer to innovations that involve distinct new knowledge or (re-)combination of existing knowledge, thus distinguishing them from incremental innovations which take minor steps and involve little novelty (Oke *et al.*, 2007; Reichstein and Salter, 2006; Keupp and Gassmann, 2013; Maine *et al.*, 2014). However, radicalness may mean different things, depending on whether the level of newness is defined at the level the world and industry (Oke *et al.*, 2007; Reichstein and Salter, 2006), or at the level of an adopting firm or adopting individuals (Damanpour and Wischnevsky, 2006; Frambach and Schillewaert, 2002). Scholars taking a broad look at the multiple levels of novelty face the challenge of sorting the broad "gray area" of innovations which lies between new-to-world level and new-to-manufacturing (adopting) firm, as the adopting firm does not necessarily know what is readily available in other firms (Reichstein and Salter, 2006).

Creation of new-to-industry or new-to-world production technologies or equipment has not been covered widely in empirical studies (Lim *et al.*, 2006), although they appear in conceptual discussions of RMTI (Lager and Frishammar, 2010). More often, empirical studies related to RMTI have focused on within-adopter organization newness and analyzed technological and organizational adaptation issues in this context (Milewski *et al.*, 2015). Such differences in levels of novelty make it difficult to compare radical innovations across contexts, e.g., with different levels of theoretical process knowledge (Linton and Walsh, 2008). Previous research does not operationalize the separation of process innovations with less and more novelty (Reichstein and Salter, 2006; Kurkkio *et al.*, 2011), but has highlighted the need for a good categorization system for avoiding the confusion caused in both practice and academia when different types of radical innovations are compared (Lager, 2002; Sergeeva, 2016; Reichstein and Salter, 2006).

The radicalness of the innovation can mean novelty also for the technology supplier, and such supplier innovations may be intended for a specific customer or generally for the market (Winter and Lasch, 2016). Creation of technology innovations has previously been portrayed as an activity between equipment suppliers and technology-adopting (manufacturing) firms (e.g. Appleyard, 2003; Hausman and Stock, 2003; Terwiesch *et al.*, 2005; Dulluri and Raghavan, 2008; Baptista, 2013). The role and activities of suppliers and other external stakeholders may vary over the innovation process (Van Lancker *et al.*, 2016; West and Bogers, 2014), the absorptive capacity of the manufacturing firm may influence how external innovation sources are leveraged (West and Bogers, 2014; Robertson *et al.*, 2012), and these naturally may have an effect on the manufacturing firms' own innovation activities as well. Van Lancker *et al.* (2016) emphasize the systemic nature of radical innovations, requiring multi-dimensional and multi-partner changes in the socio-technical system.

In conclusion, in this study we acknowledge the continuum of incremental to radical innovations (e.g. Kurkkio *et al.*, 2011), and the alternative definitions of radicalness implying novelty to the industry or world (Reichstein and Salter, 2006; Oke *et al.*, 2007), or to the adopting manufacturing firm (Milewski *et al.*, 2015; Keupp and Gassmann, 2013), with a need to develop a better categorization system (Lager, 2002). At the same time, we focus on the manufacturing firm's perspective to RMTI creation in particular, while acknowledging the active involvement of equipment supplier firms in creating the RMTI. This idea of manufacturing firm's and equipment supplier firm's mutual engagement in RMTI will require a more fine-grained operationalization of radicalness and novelty in the RMTI, as well as deeper understanding of the manufacturing firms' RMTI creation processes.

2.3 *Processes used for creating RMTI in manufacturing firms*

Empirical studies on RMTI creation processes are rare, particularly covering the full lifecycle of RMTI creation from their conception to implementation spanning across the manufacturing and equipment supplier firms. Table I reports the findings from previous empirical studies on processes in firms for the creation of new production processes and industrial equipment. None of the studies has focused on RMTI directly, but RMTIs are included in their data, and hence their findings are of interest in this study.

As is seen in Table I, existing studies have concentrated on the study of RMTI creation process phases within either the equipment supplier firm or the manufacturing firm. Both firms are, thereby, shown to play a central role in the creation process. The overall phases in the innovation creation process across both firms appear as similar, while details of the activities in either firm within the phases differ. The manufacturing firm leads the new production process concept ideation and requirement planning in the pre-study phase (Rönnberg-Sjödin, 2013; Kurkkio *et al.*, 2011), followed by negotiation, decision making and ordering within and between the two firms (Adrodegari *et al.*, 2015; Rönnberg-Sjödin, 2013), equipment engineering and construction phases in the equipment supplier firm (Adrodegari *et al.*, 2015; Rönnberg-Sjödin, 2013), finally leading to the installation and start-up of production in the manufacturing firm.

Some of the studies covered in Table I draw attention to the importance of the early phases in the RMTI creation process. For example, Adrodegari *et al.*'s (2015) study of 21 engineer-to-order equipment supplier firms from various industries emphasizes the engineering-intensive nature of the activities in the early phases of the RMTI creation process (p. 923). Kurkkio *et al.*'s (2011) investigation of the early activities in the creation process within a large metal and mineral processing firm reveals uncertainty about the process technology and equipment design leading to an iterative and experimental nature of the overall creation process. Rönnberg-Sjödin's (2013) model of typical experiences of new equipment purchase within a metal and mineral processing equipment supplier firm differs from the other studies in the more delivery-centric orientation in the process phases.

Within such an overall framework of phases in the RMTI creation process, the nature of the actual process and its activities are shown to vary for different project types. Using evidence from two cases of RMTI and five cases of innovations in non-core technologies in enabling or peripheral operations, Milewski *et al.* (2015) have argued that innovation processes differ between core vs enabling production processes. Their results from assembled-product industries show that core production process innovations have a stronger technology adaptation focus, and enabling processes have a stronger organizational adaptation focus (Milewski *et al.*, 2015). The comparison of the other studies (Adrodegari *et al.*, 2015; Kurkkio *et al.*, 2011; Rönnberg-Sjödin, 2013) draws attention to whether the process is primarily used for new equipment purchase (Rönnberg-Sjödin, 2013) or more broadly for RMTI creation (Adrodegari *et al.*, 2015; Kurkkio *et al.*, 2011). Particularly, Kurkkio *et al.* (2011) draw attention to the degree of novelty: "higher novelty resulted not only in more activities, but also in longer time-frames for individual activities, e.g. to verify ideas and problems" (p. 497). Kurkkio *et al.* (2011), however, did not explore this issue further and suggested further research to elaborate on how the processes vary in process innovation projects with different degrees of novelty.

The presently understood models for RMTI creation suggested in Table I are thus "ideal" and do not reflect how the process varies with different project types. The earlier studies describe the nature of activities within phases either from the perspective of the equipment supplier firm or the manufacturing firm, but not jointly. Some conceptual studies suggest an integrated view toward RMTI creation processes in equipment supplier and manufacturing firms (More, 1986; Lager and Frishammar, 2010). More's (1986) framework includes three sub-processes: the development sub-process within the equipment supplier firm, the adoption sub-process within the manufacturing firm and the interfacing sub-process between the two firms in which both firms work collaboratively, sharing information and resources. The conceptual framework by Lager and Frishammar (2010, p. 701) illustrates the

Table I. Summary of previous empirical research on the processes for RMTI

Authors	Perspective and empirical context	RMTI focus	RMTI creation process model	Comments, gaps
Kurkkio *et al.* (2011)	Innovation processes within manufacturing firms Qualitative data on firm-level process development practices in the early innovation stages in 4 metal and mineral processing firms	Process innovation	Informal start-up – formal idea-study – formal pre-study – formal pre-project	Partial lifecycle focus (front end only) Interaction with equipment supplier firms not covered Further research encouraged in broader samples of firms
Rönnberg-Sjödin (2013)	Collaborative opportunities in the lifecycle of machinery for process industry firms Qualitative data from 8 metal and mineral processing machinery supplier firms	New equipment development and delivery	Pre-study at the manufacturing firm – purchase negotiation for equipment and development – assembly and installation – start-up – production	Equipment supplier's perspective emphasized Focus on challenges and collaboration possibilities Further research encouraged on both sides of the dyad and entire innovation lifecycle
Milewski *et al.* (2015)	Technological process innovation and related technological and organizational adaptations in the innovation lifecycle Qualitative data on 6 examples of technological process innovations (2 involving RMTI) in 5 large assembly manufacturing firms	Technological process innovation	Ideation – adoption – preparation – installation	Emphasizes the asymmetric nature of technological vs organizational adaptations between the supplier and manufacturer RMTI cases covered as part of incremental process innovations Further research proposed to elaborate technological process innovation components
Adrodegari *et al.* (2015)	Processes within equipment supplier firms Qualitative data from 21 engineer-to-order machinery supplier firms, various industries	Engineer-to-order machinery	Quotation and order management – technical and commercial development – design – purchasing – production, assembly and testing – delivery – commissioning – after sales service. Additionally support activities	Custom-engineering effort, as part of creation activities; radicalness not evident. Does not observe ideation or prototyping activities Focus on the supplier's perspective Focus on required software support Further research suggested to develop process frameworks further for engineer-to-order industries

RMTI development phases that occur in equipment supplier firms, followed by the operational lifecycle phases in manufacturing firms. Winter and Lasch (2016) recommend evaluating supplier innovations before acquiring external resources for innovations. Such an integrative view of the RMTI creation process across the manufacturing firm and the equipment supplier firm is rare in empirical studies, and empirical research has been called for (Lager and Frishammar, 2010).

A core issue in the RMTI creation process appears to be the division of work between the technology-adopting manufacturing firm, and the equipment supplier firm. Von Hippel (1978) suggested equipment supplier firms to initiate their process for novel product development inside the manufacturing firms (with distinguished lead users, or early adopters of innovations). With the lead users, the suppliers can receive new equipment ideas and concepts from the customers rather than invest their own resources in idea generation and development (Von Hippel, 1978). Baldwin *et al.* (2006) modeled the RMTI process to be initiated at the manufacturing firm that develops the first prototype equipment in-house, uses it and even markets or sells copies to other manufacturing firms. Eventually, a market is created for the new process technology, attracting equipment supplier firms toward the technology's further refinement and development, leading to new industrial products and solutions in their business. To achieve a complete picture of the RMTI creation processes, there is a need to understand both the technology supplier's and the manufacturing firms' perspectives to the processes.

In conclusion, previous research describes the phases and activities in RMTI creation, but covers these processes only partly, dominantly from the equipment supplier's perspective. The findings indicate the presence of different types of creation processes based on project type, but differences of RMTI processes across different project types remain to be further explored. The few existing empirical studies on RMTI creation processes have investigated RMTI among other types of process innovations, including incremental innovations and innovations in non-core processes (Kurkkio *et al.*, 2011; Rönnberg-Sjödin, 2013; Milewski *et al.*, 2015). While pointing out the importance of both the technology-adopting manufacturing firms and equipment supplier firms in the RMTI creation processes, the earlier studies do not sufficiently cover the participation patterns of the two firms in different RMTI creation processes.

3. Research method

3.1 Research design

A qualitative research strategy was used for the exploratory research task, with the intent of generating new knowledge on alternative RMTI processes. A purposive sampling strategy was followed, to obtain information relevant to the research task (Bryman, 2012) concerning various RMTI projects. Emphasis was placed on gathering data from a variety of firms that had recent experiences with implementing new technology in their core production processes, with RMTI project as the unit of analysis.

Firms that had active process R&D and that had adopted novel technologies, such as nano-technology and additive manufacturing, which are considered topical manufacturing innovations (McKinsey Global Institute Report, 2012, p. 10), were included. A second search strategy was to contact production development managers and production directors in manufacturing firms regarding their RMTI experiences. Altogether, 17 suitable firms were identified and contacted as prospective contexts for RMTI projects. In the final sample, firms of different sizes (fewer than 50 employees – more than 10,000 employees) and in different industries (e.g. equipment, assembly and process manufacturing, metals, electronics, nano-technology, luxury goods and ship building) are represented to achieve variety as well as identify common patterns across the RMTI projects. The companies are well-known firms, and some of the RMTI projects resulted in patents.

Within the firms, we sought for such knowledgeable informants that were closely involved with a recently completed RMTI project, particularly from the perspective of innovation decision making and leadership. The interviewees are directors and managers who had the best first-hand knowledge of the RMTI project in the specific firm (1–2 per project). In this way, the interviewees are the best experts to discuss these projects, and often – particularly in the small and medium-sized firms – they were the only persons that could tell about the innovation and the RMTI creation process. As a contrast to the previous in-depth case studies, this exploratory study builds upon the first-hand knowledge of these informants and seeks variety and breadth of RMTI projects. The total number of interviews was 23, and 23 RMTI projects were discussed as part of them. Table II summarizes the background information of the firms and interviewees. Table AI describes the 23 RMTI projects in more detail.

3.2 Data collection

Semi-structured interviews were used for the primary data collection. They allow the investigator to probe interesting and important topics that arise based on the interviewees' experience (Bryman, 2012, p. 471). The interview outline (Appendix 2) had four main thematic sections: background of the interviewee and firm; the drivers and process of emergence of the selected RMTI project; RMTI development; and RMTI implementation, including challenges in its realization. The timing, duration and different phases of the process, the roles of individuals, and other influences were discussed for all RMTI projects. Each theme included specific questions, but the outline was largely used as a guideline for offering information and setting expectations for the scheduled interview meeting. Based on the first two interviews, the outline was slightly modified.

The interviews primarily took place in meeting rooms on company premises, and they were recorded with the permission of the interviewee and subsequently transcribed. After each interview, the first author reviewed the interview content, and compared it with earlier interviews, taking general notes on emerging themes and code categories as a preparatory step for the actual analysis and to assess the sufficiency of data. Data saturation was reached during the latter phase of the interviews, meaning that

	Equipment supplier firms	Manufacturing firms: equipment adopters/users
Nr. of firms	3	14
Range of firm sizes (in turnover MEUR)	Smallest: 7; median: 21; largest: 2,900	Smallest: 6; median: 500; largest: 31,000
Range of industries	Machine tools, nano-technology, paper and pulp	Sheet metals, assembled machines and machine components (industrial vehicles, ship engines, valves), electric motors and generators, electronics, semiconductor, luxury goods, paper and pulp, furnace
Range of technologies involved	Atomic layer deposition, paper-web heating technology	3D printing, induction heating, lignin production technology, dry etching, 3D laser cutting technology, robotics and automation, atomic layer deposition, gasification (renewable energy production) technology, etc.
Nr. of RMTI projects	6	18 (one overlapping with the supplier firm's RMTI project)
Nr. of interviewees	4	19
Job positions of interviewees (examples)	Vice president (business unit), business director, sales manager	Production director, Sr. production development manager, manufacturing manager
Average duration of interviews (minutes)	60 min. per interview (total duration: 312 min)	60 min per interview (total duration: 1,005 min)

Table II. Interview data collection

the appearance of new information on RMTI experiences was rare in later interviews (Guest *et al.*, 2006), and the number of interviews was determined as sufficient to achieve thematic exhaustion (Bryman, 2012).

3.3 Data analysis

The data were analyzed using an inductive approach, examining both the specific RMTI project and its contextual setting. The RMTI projects were numbered (1–23, see Table AI), and they are referred to using these numbers when reporting the key findings. The interview data were first reviewed to derive analysis categories or themes (Bryman, 2012). The RMTI project characteristics were analyzed in terms of innovation novelty, roles of the manufacturing and supplier firms, activities in initiating and creating the RMTI, and activities in developing and implementing the RMTI.

An in-depth systematic comparative analysis of the RMTI projects was carried out in four phases, including a search for support from or framing in previous literature. First, in order to be able to compare the RMTI projects, we mapped the types of RMTI by coding the interviewees' expressions of novelty for the manufacturing firm, for the equipment supplier and in the industry. Table III shows the approach for coding novelty in the RMTI projects. After this, the RMTI projects were categorized into low, medium and high novelty as shown in Table IV. As all projects were through the sampling criterion new to the manufacturing firm, it was not coded separately.

In the second analysis step, we identified the different activities included in the RMTI creation processes in all the RMTI projects, considered the similarities and differences across the projects, and clustered the RMTI projects with similar processes features. Similarities were evident in the investment decision and implementation phase, whereas particularly the front ends and development phases differed significantly. Consequently, we identified three types of RMTI creation processes (i.e. clusters of RMTI projects):

(1) A procurement-type process, if the equipment existed, if there was previous knowledge on its use and the suggested application, and if the RMTI process featured a front end emphasis for the manufacturer, with a deep pre-study, feasibility analysis, investigation of technology, and perhaps also process conceptualization, prior to a fairly ordinary purchasing and implementation phase.

(2) A development-type process, if the process included engineering work for a complete functioning equipment and, thereby, involved the manufacturing firm into the development activities, including various design, prototype, testing, re-working and installation activities.

(3) An invention-type process, if it required process R&D and inventions before development and validation and, consequently, engaged the manufacturing firm and the supplier(s) in a much deeper and complex cooperation already quite early than in the other types of processes. The detailed differences in the activities of these process types as well as included RMTI projects are reported in the results section in Table V.

Third, we identified the activities of the manufacturing firm and the equipment supplier firm as well as in their cooperation during the creation processes. For this third task, the basic idea in More's (1986) conceptual framework was adopted and adapted based on the previous phases of the analysis, as it was the only framework acknowledging that the idea for the RMTI may emerge in either the supplier or the manufacturing firm. The names of the activities in the framework were adapted to match the empirical findings. All 23 projects were mapped separately, and three representative examples were selected to illustrate the flow of activities between the two firms for each RMTI process type. To visualize the result

Code	Explanation	Example quotation
New to equipment supplier	The interviewee expressed that the supplier had never developed or used such a technology	"No I think this was totally new, also for them [the supplier]. Of course they have knowledge for the robots" manufacturing firm, Project 13 "We were in an area, or an unexplored area of process beyond the process window where we used to be. So that was completely new for everyone" equipment supplier firm, Project 3
Known by the equipment supplier	The interviewee expressed that the supplier knew the technology beforehand	"I think the machine itself, it is already a product. So it is not that someone had to invent it or something like that, I think they have been producing this for some other customers […]" manufacturing firm, Project 10
Established technology in the specific industry (custom engineering using known technology)	The interviewee expressed that the technology was already known in the manufacturing firm's industry	"It's not a new method. I think that we didn't do any innovation in the technology I would say. But designing the machine, how it works, and what kind of programs are used, and, all the variations […], there I think it was the need for designing […]" manufacturing firm, Project 22 "We had the needs now and investigated what was the best technology at the moment to do it [and it was available in the industry]" – manufacturing firm, Case 8
New technology in the specific industry (technology or its application invented)	The interviewee expressed that the technology was new also for others in the specific industry – no-one in the industry had developed or used it before	"We made some market studies, nothing really big but, to the knowledge we had, it showed up that there is nothing concrete around the world. Nobody you can buy something from," equipment supplier firm, Project 3 "But the problem was that there was no experience in that kind of scale as we are implementing, so there was the risk. There was no implementation in this kind of an industry earlier" manufacturing firm, Project 14

Table III. Coding framework for assessing technology novelty in the RMTI projects

in an effective way and to enable comparison, ordinary flow-charts are reported instead of the original matrix format (Figure 3).

Finally, we mapped the use of different creation process types for different RMTI types. This result combines the results from the first two analysis steps and is reported in Figure 4 and in the text. Quotes from the interviews are used, and summary tables, process descriptions and flow-charts were developed to compress and illustrate the findings.

Actions were taken to enhance the validity of the research. Concerning confirmability, a thematic interview protocol was used for all interviewees, the interview frame was developed into its final form through the first few interviews, and the interviews were recorded and transcribed. Reliability was enhanced by selecting informants that had first-hand knowledge of the RMTI projects, using a consistent data collection protocol, and building a simple analytical frame for the analysis. To enhance the credibility of results, the novelty and process categorization frames were validated

Table IV. Clustering of RMTI projects to identify different levels of novelty

New to mfg. firm	New to equipmt. supplier firm	Established in the specific industry: custom engineering using known technology	New to the specific industry: technology or its application invented	RMTI type	RMTI projects in the sample (see Figure 1 for the content of RMTI projects)
x		x		Low-novelty RMTI	8, 10, 16, 17, 19
x	x	x		Medium-novelty RMTI	5, 6, 11, 13, 20, 21, 22
x			x	Medium-novelty RMTI	2
x	x		x	High-novelty RMTI	1, 3, 4, 7, 9, 12, 14, 15, 18, 23

Note: "x" signifies the novelty features that characterize the RMTI type

Table V. Three processes for creating RMTI identified in the studied RMTI projects

Process type	Process description
Procurement-type process	**Pre-study** → **Procurement** → **Implementation** Pre-study: • Process conceptualization • Technology investigation Procurement: • Investment planning and decisions • Investment preparation • Order equipment • Delivery, install, trials Implementation: • Ramp-up • Learn to use RMTI projects in the sample: 2, 8, 10, 16, 17, 19
Development-type process	**Conceptual phase** → **Development phase** → **Implementation** Conceptual phase: • Process conceptualization • Equipment concept development, including technology selection • Equipment prototype (proof-of-concept models) Development phase: • Investment planning , preparation and decisions • Contract • Equipment engineering, designing • Construction, trials, possible rework • Delivery, installation • Production trials, possible rework Implementation: • Ramp-up • Learn to use, possible adaptations RMTI projects in the sample: 5, 6, 11, 12, 13, 15, 18, 20, 21, 22
Invention-type process	**Creation of new process know-how** → **Process concept validation** → **Investment consideration** → **Equipment Development** → **Implementation** Creation of new process know-how: • Discovery – Basic research • Application R&D (technical, lab-scale) • Discussions exploring new process application • Create consortium for development of idea Process concept validation: • Equipment concept development • Proof-of-concept level prototype, e.g., demo plant • Revise, improve process concept and equipment concept Investment consideration: • Address and solve critical areas of risk and uncertainty • Investment planning • Decision, negotiation, contract Equipment Development: • Equipment design and engineering • Construction • Trials, possible redesign, rework • Delivery, installation • Production trials, possible redesign, rework Implementation: • Ramp-Up • Learn to use, possible adaptations RMTI projects in the sample: 1, 3, 4, 7, 9, 14, 23

through reporting the findings to the interviewees in a practitioner-oriented report, organizing a workshop to present the findings, and requesting for possible feedback. Changes were not requested by the interviewees at this stage. To enhance transferability and application of results, we have delimited the focus to RMTI as the innovation type, purposely selected companies that have participated in RMTI recently, and invited also new participants to the results workshop. Remaining validity limitations are discussed in the concluding section.

4. Findings

4.1 Types of RMTI

The sample of 23 RMTI projects was heterogeneous, as it covered examples from different industries, involved different process technologies, and included differences in the levels of novelty, ranging from adopting a widely known technology to creating new inventions. As shown above, all RMTI projects were "new-to-manufacturing firm," while "new to the supplier," "known by the supplier," "new technology in industry" and "established technology in industry" emerged as the differentiating novelty themes in the interview transcripts. The clustering of firms on this basis revealed three types of RMTI based on the level of novelty (Table IV).

Low-novelty RMTI projects involve newness at the level of the manufacturing firm changing to a new-to-firm technology for their core production process. For these projects, no newness was involved at the level of the equipment supplier firm, and the technology and related equipment represents "a standard product" for the equipment supplier firm and also more generally in the industry. The equipment involved can therefore be selected from the product catalogues of the equipment supplier, and usually the best equipment suppliers are well-known in the industry. For example, in RMTI Project 10, a flexible automated stacking equipment was implemented, and as such automation existed already, the main thing was to find a suitable supplier and customize the system for the manufacturing firm's product range. The equipment supplier can provide previous customer references, arrange benchmarking visits to other installations of the same or similar equipment, and arrange systematic training for the manufacturing firms.

Medium-novelty RMTI projects involve tailor-made, special-purpose equipment engineered dominantly using known technology. These RMTI involve newness at the level of the equipment concept, and there are no ready solutions available for direct purchase, e.g., by selecting from suppliers' catalogues. In addition to newness at level of the manufacturing firm, medium-novelty RMTI projects typically involve newness at the level of the equipment supplier firm that must develop the application for the first time; however, the core technology was not invented as part of the RMTI, and the development effort involved engineering using known technology principles and the use of commercially available components. For example, in RMTI Project 20 the joining technology existed and the supplier firm had to do inventive design work and engineering, to build the solution for the customer. Such RMTI often involve equipment suppliers who have experience and expertise in the technology involved, e.g., testing equipment suppliers, small machine tool builders and automation systems builders.

RMTI Projects 2, 12, 15 and 18 did not completely match the criterion described above for medium-novelty RMTI. In line with the other medium-novelty RMTI projects, Projects 12, 15 and 18 involved engineering of unique equipment, developed for the first time by the equipment supplier firms involved in these projects. However, the technology was not invented in these projects, but technologies and process concepts were explored outside of their specific industry and implied a novel process concept in the projects' specific industries. Since piloting a novel process concept is a feature of high-novelty RMTI (as described further below), these three projects were categorized as high-novelty RMTI projects. Project 2 resembles these projects, with respect to exploring and piloting of a novel process concept within their industry. In Project 2, advanced 3D printing technology equipment was implemented, and the equipment was adapted as part of a trial for mass printing of wax castings. The traditional process in the manufacturer's industry involved the use of die casting and pressure-injection technologies to create mass copies of wax castings based on a master prototype piece. In comparison to RMTI Projects 12, 15 and 18, the RMTI Project 2 lacks the design and development of the equipment itself, and the equipment procured was a standard solution for the equipment supplier firm. Taking into account the simultaneous presence of features of low and high-novelty RMTI in this project, it has been identified as a unique medium-novelty RMTI project.

High-novelty RMTI projects involve the invention of a new technology or an invention that enables a novel application of an existing technology that is patentable. They involve newness for the manufacturing and equipment supplier firms and newness at the level of the technology or application and thus newness at the global or industry level. Ready-made solutions do not exist, the manufacturing firm and the technology supplier do not have previous experiences with the technology, and there are no benchmarks to visit and learn from. For example, in RMTI Project 7, a new solution was designed for material extraction in pulp processing, the technology was patented, and the implementation required multiple breakthroughs before turning it into a production concept. Technology patents were involved in nearly all RMTI projects in this category, with the exception of Projects 12, 15 and 18. In addition to the development of the equipment concept, high-novelty RMTI projects involved the creation of new process know-how and piloting the use of a non-proven technology in an industrial production process. Figure 2 illustrates the 23 RMTI projects and the level of novelty for each project.

4.2 Types of RMTI creation processes

The 23 RMTI projects differed in terms of the processes in which the RMTI was created. Some projects involved a shorter creation process and some a longer process with additional

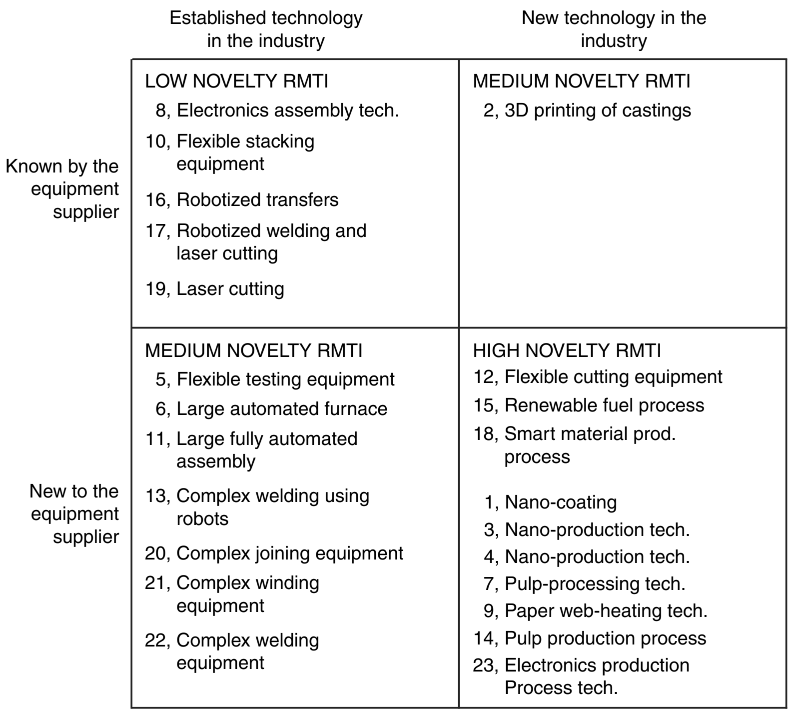

Figure 2.
Types of RMTI and degree of novelty identified in the studied RMTI projects

activities and phases. The creation process for each project was outlined based on the interview transcripts, and the processes were compared for commonalities and differences. The analyses revealed three types of RMTI creation processes, which were labeled procurement-type (six projects), development-type (ten projects) and invention-type processes (seven projects). Table V summarizes the basic features of the RMTI creation processes and the RMTI projects that best match each process type.

The procurement-type process of RMTI creation is where both the creation of new process know-how and new equipment concepts are missing, and it primarily involves identifying the suitable technology, ordering and implementing it, and learning to use it. As the RMTI involves a shift in the core production technology used in the firms, it involves an early phase of new process conceptualization "outside of the box" of current ways to create products. The new-to-manufacturing firm process concept is followed by technology investigation, i.e., a detailed investigation of the available technology and equipment. For most projects, the technology choice was immediately clear, and the pre-study phase focused on searching for the most suitable equipment and supplier. For some projects, the pre-study phase involved interactions with equipment suppliers regarding their equipment technology and test samples (Projects 2 and 8) or visits to reference plants where similar technologies had been successfully installed by the same supplier (Project 17).

The pre-study phase leads to investment planning and decision making, including quotations from alternate suppliers, comparisons and negotiations for optimal supplier and solution selection, planning the financing of the equipment, refining the business case, and justifying the purchase, e.g., pay-back calculations, for approval by management. The timing of the decision is influenced by business strategies, business environments (e.g. recessions) and investment decision makers' involvement in the early stages. The phases following the investment decision and before the ramp-up were brief and smooth from the interviewees' perspectives. For example, the interviewee for Project 8 stated "[…] it's more like implementation. Order the device and make sure that they are as you ordered them and then assemble them and then ramp-up the production; it's more like doing then." For three projects (8, 10 and 17), engineering was required for the modular equipment, whereas in other projects (2, 16 and 19), the equipment supplier delivered the ordered standard equipment. Collaborative efforts were involved during the installation, production trials, training and ramp-up. Most interviewees discussed a period of one year following equipment installation during which the plant employees learned to use the new technology equipment with confidence, e.g., making small improvements and regulating settings on their own.

The development-type process of RMTI creation involves the creation of a new equipment concept – designing an approach to implement a certain process know-how in a specific manufacturing context – and involves engineering work and specification development. These projects began with new process conceptualization in the manufacturing firm. Compared to projects using the procurement-type process, projects with the development-type process were less clear regarding the feasibility of the equipment concept in the process conceptualization phase, and in some projects, there was no clarity regarding the technology that should be selected initially. For these projects, the equipment concept development activities were more technical and involved detailed investigations of potential solutions and methods. At the end of process conceptualization phase, proof-of-concept, e.g., prototypes (Project 5 and 12), detailed drawings (Project 6) or detailed plans for proposed RMTI implementation (Project 11) led to the initiation of investment planning work.

The remaining phases of the development-type process were similar to the procurement-type process with the addition of a design phase. The design work involved engineering for a few months at the equipment supplier firm and required interaction and feedback from the manufacturing firm to develop detailed specifications. The subsequent testing stages were critical as errors, rework and development issues could arise, which did arise for some projects (6, 11, 15 and 22). For Projects 18 and 12, there were uncertainties related to the equipment concept until the production trials were completed.

The invention-type process of RMTI creation includes the creation of new process know-how in addition to new equipment concept development. This process has a longer front end, involving basic research followed by application-oriented research to determine whether the new process application is feasible for real industrial use. These projects began with new knowledge and discoveries about process know-how from scientific research within either the equipment supplier or manufacturing firm, or in joint research projects in industrial research networks. The initial phase involved discussions on the potential of utilizing the new process know-how and search for the right types of partners (e.g. willing to take risks, be leaders and bring in needed experience in technical areas) needed for development. Concept validation via proof-of-concept prototypes, industry-scale prototypes and detailed implementation plans (Projects 1, 3, 4, 7, 9 and 14), at times involving concept improvement iterations, was perceived as a turning point, making the new RMTI concepts appear to be more feasible. It created the rationale for the pre-study phase on commercial, economic and construction issues in the manufacturing firm. The investment planning considerations and the following stages involved activities similar to those described for the procurement-type and development-type RMTI processes. For some projects (e.g. Projects 3 and 7), chance events had a significant impact, and active leadership and communication were needed (promoting the concept and its opportunity over its risks), leading to the investment decision of the manufacturing firm.

The equipment engineering, design and construction phases involved a period of intense activities for the equipment supplier firm. Testing was described as a critical phase in which unplanned, unexpected errors emerged, causing the need for redesign (at times, new development issues occurred) and rework. Following the ramp-up phase, there was a learning period of up to one year in which the manufacturing firm employees gained experience in using the new technology and becoming confident in equipment maintenance. During this period, small adaptations in the equipment were made in Projects 1, 3, 4, 7 and 14.

4.3 Activities of manufacturing and equipment supplier firms in RMTI creation processes

The creation of RMTI in the projects involved at least two organizations: a manufacturing firm and an equipment supplier firm. For some projects, a research institute played the role of the manufacturing firm as a financer of the development work and the buyer of the equipment developed during the RMTI project. For some projects, additional technology expert organizations participated, such as firms specializing in the technology, research institutes or universities. Searching for suitable and interested partners in the development of the process technology and arriving at a contract between the firms were important turning points during the RMTI creation process.

As the manufacturing firms' and the equipment supplier firms' individual activities and collaboration appeared to be a central component of RMTI creation, we mapped the firms' activities and further analyzed the processes of the 23 RMTI projects. Figure 3 summarizes the results of the most typical RMTI project examples. The activities at the intersection of the two actors indicate collaboration. Projects 19, 13 and 7 were selected as examples to illustrate the typical process flow for the three process types.

As shown in the figure, the early period of Project 19 (example of procurement-type process) consisted of pre-study phases including process conceptualization, investigation of available technology and equipment, investment considerations and decision, which largely took place within the manufacturing firm. The equipment supplier firm was contacted to

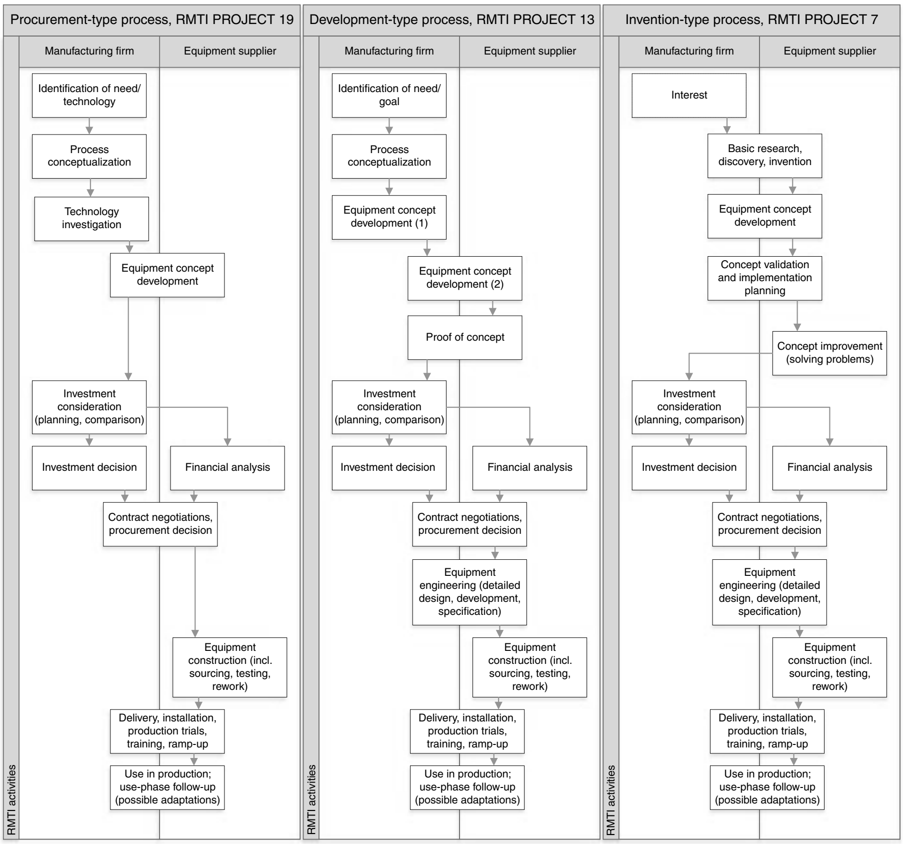

Figure 3. Mapping of manufacturing firms' and equipment supplier firms' activities for the three types of RMTI creation processes (example Projects 19, 13 and 7)

collect information used to identify the best available equipment and supplier during equipment concept development. The later phases after the investment decision involved the independent construction of the equipment at the equipment supplier firm, collaborative installation and training phases, and ongoing learning during the first year of using the new technology in the manufacturing firm. This was the dominant pattern for all projects with procurement-type process. The only exceptions were whether dialogue with the equipment supplier occurred before need identification and process conceptualization within the manufacturing firm (Project 10) and whether the equipment supplier supported and participated in the ongoing learning of the use of the equipment after ramp-up and when adaptations were needed (Projects 2, 10 and 17).

During the early phases of the RMTI projects that included a development-type process, such as Project 13, there was a more collaborative approach during equipment concept development compared with the procurement-type process; however, there was a larger variation across the RMTI projects in the ways the equipment concept phase was carried out. Of the ten projects, the manufacturing firms either shared their needs with the equipment supplier firms (specialized tool builders) and asked them to develop and provide equipment concept solutions (Projects 6, 12, 20 and 21), developed their own equipment concepts and interacted with equipment supplier firms at a later stage (Projects 13, 15, 18 and 22), or jointly developed the concept by involving the equipment supplier firm in early stages (Projects 5 and 11). The additional equipment engineering phase following the contract between firms was concentrated within the equipment supplier firm for five projects in this cluster and was more interactive and collaborative for the other five.

For RMTI projects with an invention-type process, such as Project 7, the early period involved scientific research and new knowledge generation. There were considerable variations regarding where the discovery occurred: during R&D activities within manufacturing firms (Project 14), within the equipment supplier firms (Projects 1, 3, 4 and 9) or within research projects in an industry network of firms and research institutes (Projects 7 and 23). Accordingly, the process was initiated by either the manufacturing or equipment supplier firm or was initiated outside of the two firms (in a research network). The early process phases involving process conceptualization, equipment concept development and validation could be carried out within either firm (7, 9 and 14), in close collaboration (4), or with some interaction between the two firms (1, 3 and 23). The seven projects with an invention-type process also varied regarding whether the detailed engineering and development phase was completed primarily within the equipment supplier firm (1, 3, 9 and 14) or involved more interaction between firms (4, 7 and 23). Overall, the participation of the equipment supplier firms in the invention-type processes was quite active during the early phases and clearly more active than in the two other types of processes. The manufacturing firm consistently played the role of a financer (and thereby the risk taker) for the detailed engineering and development of the equipment concept, as actual development work on the details of the equipment concept began after the contract was made.

The above analysis suggests that collaborative activities between the manufacturing firm and the equipment supplier firm increase in the project front end from procurement-type to development-type to invention-type processes. For example, the long pre-study phase is largely concentrated within the manufacturing firm for the procurement-type process, while equipment supplier firms are actively involved in the stage of equipment concept development for the development-type process and in the basic technology discovery and application R&D phases for the invention-type process. Furthermore, Figure 3 illustrates that RMTI creation activities differ slightly from the perspectives of manufacturing and equipment supplier firms. While some activities in the overall process, such as investment consideration, decisions within each firm at the time of contract and equipment construction, are concentrated within either firm, both firms play a role in the initiation, conceptualization and development of the RMTI until its implementation.

4.4 Different process types for different RMTI types

The three types of RMTI creation processes differ in the number of phases and the intensity and number of activities in similar phases. The number of phases increases from the procurement-type to development-type to invention-type processes. For example, the equipment concept development and equipment engineering/design phases are missing in the procurement-type process but play an important role in the development-type process. Similarly, the discovery, application R&D and process concept validation phases are missing in the development-type process but are highlighted in the invention-type process.

The use of different process types across the different RMTI types was mapped to identify potential patterns in the RMTI processes. Figure 4 summarizes the processes for the different types of RMTI projects. The mapping reveals a pattern: an overlap between RMTI types and RMTI process types. Of the high-novelty RMTI projects (1, 3, 4, 7, 9, 12, 14, 15, 18 and 23), seven projects had the invention-type RMTI creation process (1, 3, 4, 7, 9, 14 and 23). Of the eight medium-novelty RMTI projects (2, 5, 6, 11, 13, 20, 21 and 22), seven projects included the development-type process (5, 6, 11, 13, 20, 21 and 22). While there were five low-novelty RMTI projects (8, 10, 16, 17 and 19), six projects included the procurement-type process (2, 8, 10, 16, 17 and 19). Exceptions to the pattern are indeed the four Projects 2, 12, 15 and 18 described earlier in Section 4.1

	Established technology in the industry	New technology in the industry
Known by the equipment supplier	LOW NOVELTY RMTI 8, Procurement 10, Procurement 16, Procurement 17, Procurement 19, Procurement	MEDIUM NOVELTY RMTI 2, Procurement
New to the equipment supplier	MEDIUM NOVELTY RMTI 5, Development 6, Development 11, Development 13, Development 20, Development 21, Development 22, Development	HIGH NOVELTY RMTI 12, Development 15, Development 18, Development - - - - - - - - 1, Invention 3, Invention 4, Invention 7, Invention 9, Invention 14, Invention 23, Invention

Figure 4. Types of creation processes identified in the studied RMTI projects, divided by the type of novelty

The overall pattern revealed the exceptions of Projects 2, 12, 15 and 18, and we analyzed them further to identify potential explanations. The procurement-type process for Project 2 is understandable through its familiarity for the supplier but novel application domain in a new industry for the manufacturing firm and, thereby, the need for piloting in a high-volume industrial use. It, however, did have a fairly long pre-study, long implementation and ramp-up period, and needs for later technology adjustments, compared to ordinary procurement-type processes in the category of low-novelty RMTI. Projects 12, 15 and 18 involved novel applications of existing technology for a different use requiring considerable engineering efforts for the development of the equipment. These high-novelty RMTI projects did not need the long research phase typical to invention-type processes as the firms sought for technologies outside of their own industry, used in other applications aligned with their need. Thereby, they appeared to utilize the development-type RMTI process. While this implied suppliers' low knowledge of the application and high requirements for engineering and design for the manufacturer's specific system, it saved time in the research and pre-study phase.

5. Discussion

5.1 Different types of RMTI projects

In this study, we have purposely centered on the radical innovations in manufacturing firms' core production technologies, to develop knowledge on the processes and practices needed, for the manufacturing firms to benefit from equipment suppliers' offerings. The differentiation of RMTIs from innovations concerning peripheral or enabling processes (Bessant, 198) and incremental innovations (Milewski *et al.*, 2015) imply that, through RMTI, manufacturing firms invest into their core productive capabilities and capacity (i.e. critical resources), which requires their proactiveness also in ideation and development. Thereby, RMTI cannot be treated just as technology adoption (Raymond and St-Pierre, 2005), implementation (Khazanchi *et al.*, 2007) or diffusion (Antonelli, 2006). As also RMTI projects vary, we need to understand how each of them can be managed successfully and why, depending on the project type.

The preparatory step for responding to the research questions included mapping the RMTI projects in terms of their novelty. Three types of RMTI were identified based on the level of novelty involved. Our inductive analysis revealed that "newness to equipment supplier firms" together with "newness-to-manufacturer's-industry" enables categorizing radical innovations into those with low, medium and high novelty and, thereby, supplements the adopter's view that may be restricted through the manufacturing firms' limited awareness of existing technologies. This approach was useful in differentiating between the 23 RMTI projects, and there was considerable within-category homogeneity regarding the process experiences of the managers involved in the creation of RMTI. The results suggest that the categorization system used could be helpful in assessing and mapping RMTI creation projects in firms and thereby selecting the appropriate processes.

The developed novelty categorization offers a solution to the challenge described in previous studies on radical innovations regarding the broad gray area of innovations between new-to-world innovations on one extreme and new-to-adopter firms only on the other (e.g. Reichstein and Salter, 2006). Taking into account the technology novelty for the supplier as well as to the manufacturing firm's specific industry more broadly offers a logical categorization for radical innovations, thereby evading the ambiguous criteria for medium-novelty innovations, such as those with a moderate degree of changes in products and production processes (Sergeeva, 2016) or those with incremental changes in plant equipment with incremental newness to the world (Lager, 2002).

5.2 Three alternate processes for RMTI creation in firms

The first research question inquired the types of processes manufacturing firms use for RMTI creation. While previous research has partly covered the front end phases of process innovations (Kurkkio *et al.*, 2011) and core phases in new equipment procurement (Rönnberg-Sjödin, 2013), this study investigated the RMTI creation process broadly, revealing different types of RMTI processes, here labeled as procurement-type, development-type and invention-type processes based on their core challenge.

The comparative analysis yielded a broad and detailed picture of the processes for RMTI creation and, thereby, contributes by offering additional information on the activities within the different RMTI processes. The procurement-type process is similar to the process described by Rönnberg-Sjödin (2013) and involves a long pre-study phase within the manufacturing firm, including identification and investigation of alternate technologies for a core production operation, followed by ordering and implementation phases. Development-type process resembles the process discussed by Adrodegari *et al.* (2015); it involves concept development and engineering of the equipment, besides the pre-study and implementation phases. Invention-type process includes similar features as the iterative process reported by Lim *et al.* (2006) and emphasizes front end activities as reported by Kurkkio *et al.* (2011), as it involves the development of new process know-how and new technology as part of the front end phases. The implementation stages (testing, production trials and ramp-up) involve re-work and possibly redesign and development for the development-type and invention-type RMTI processes.

The findings add to previous research by offering detailed knowledge for each of the process types involved in creating RMTI. While the generalizability of previous RMTI process research has been limited to a specific industry, technology or innovation phase (Kurkkio *et al.*, 2011; Frishammar *et al.*, 2013; Rönnberg-Sjödin, 2013; Milewski *et al.*, 2015), the current findings offer rich evidence of different technologies and industries, cover the entire RMTI processes, and provide empirical evidence for the applicability of each process type. One of the key contributions, in particular, deals with emphasizing the manufacturing firm's proactive role and collaboration with equipment suppliers in all types of RMTI, which is discussed next.

5.3 Roles of manufacturing and equipment supplier firms in the RMTI creation process

Among the key contributions of this study is the identification of manufacturing firms as active and influential actors in creating RMTI. Prior research has focused on the role of manufacturing firms as lead users and idea generators (Von Hippel, 1978) and adopters and implementers of technology developed elsewhere (e.g. Raymond and St-Pierre, 2005; Khazanchi *et al.*, 2007; Swink and Nair, 2007; Sinha and Noble, 2008; Stock and Tatikonda, 2008; Karlsson *et al.*, 2010; Da Rosa Cardoso *et al.*, 2012; Gomez and Vargas, 2012). Manufacturing firms are perceived to have a small or non-existent role in the RMTI creation phases (Damanpour and Wischnevsky, 2006; Lager and Frishammar, 2010) or they have been seen as first prototype developers, sharing their technologies with other manufacturing firms and transferring the technology to be further developed by suppliers (Baldwin *et al.*, 2006). In contrast, the results of this study highlight the role of manufacturing firms as active co-creators of RMTI, as they initiated particularly the procurement and development-type RMTI processes, took contact with equipment supplier firms, financed the development and engineering work, and took an active role in collaboration during concept development and engineering work. This co-creation aspect is novel and will deserve also further research attention.

Where previous research has studied the technology innovation process often from the equipment supplier's perspective (Rönnberg-Sjödin, 2013; Adrodegari *et al.*, 2015), this study has emphasized the manufacturing firms' view, also to suppliers' activities. Even if the equipment supplier firms would initiate the RMTI creation process, they require interested manufacturing firms to participate in further development of the equipment concept, to invest both money and effort in the new technology, and to take the risk with piloting the use of the novel technology and its processes. As the initiation, sponsoring and context-specific use of a novel technology are strategic tasks of RMTI creation, a manufacturing firm's role in RMTI creation becomes critical. By adapting a framework used in another context (More, 1986) with RMTI specific content, the manufacturing firm's and equipment supplier's patterns of action and interaction were revealed and differentiated by the RMTI process type. The more refined role of manufacturing firms in RMTI creation presents new opportunities for further research to complement the product development centric equipment suppliers' viewpoint.

The findings also emphasize the role of equipment supplier firms in RMTI creation as experts in technology and the construction of industrial equipment. The findings thereby deviate from studies suggesting that RMTI are internally developed within manufacturing firms (Gopalakrishnan and Bierly, 1999; Milewski *et al.*, 2015; Baldwin *et al.*, 2006). Rather, an integrated view on the creation sub-processes occurring within and between manufacturing and equipment supplier firms is proposed (e.g. More, 1986). Understanding the collaboration between the manufacturing firm and the equipment suppliers as well as its different patterns across different RMTI projects offers a valuable perspective for further research on the processes and strategies of RMTI creation.

5.4 RMTI creation process types based on the level of novelty

The second research question asked the ways RMTI creation processes vary across different RMTI projects. The findings revealed a clear pattern of employing specific RMTI creation processes for specific RMTI project types, namely, the dominance of procurement-type processes for low-novelty RMTI, development-type processes for medium-novelty RMTI and invention-type processes for high-novelty RMTI. While previous studies have reported divergences of RMTI creation processes for different types of RMTI projects in limited industrial settings (Kurkkio *et al.*, 2011; Rönnberg-Sjödin, 2013), this study has contributed by offering illustrative empirical evidence on the differences in processes across a variety of RMTI types. The results suggest adopting a contingency view to RMTI creation, i.e., differentiating between RMTI creation processes depending on the novelty and engineering effort required by the equipment supplier firm and the requirement to invent novel process technology.

The findings indicate that the collaborative activities between the manufacturing firm and the equipment supplier increase from procurement-type to development-type and invention-type innovations, and thereby also from low to medium to high degrees of novelty. This trend offers empirical support concerning open innovations: if radical innovations benefit from openness and require partners' access to organization-specific knowledge (Huizingh, 2011; Van Lancker *et al.*, 2016), this understanding could be well-designed into differentiated RMTI processes, depending on the degree of novelty. With the focus on RMTI specifically, our findings emphasize that novelty must be understood in a holistic way to select the right RMTI process – novelty is not just newness to the manufacturing firm, but newness to suppliers and the manufacturer's specific industry as well. The activity descriptions in Figure 3 offer a starting point for developing the partners' roles in the RMTI processes further. The findings, in particular, encourage differentiating the innovation support mechanisms and collaborative practices depending on the RMTI process type.

6. Conclusion

6.1 Contributions

With the goal of increased understanding of the creation processes for RMTI in firms, this study has responded to the call for additional empirical studies on the processes by which technology and process innovations take place in manufacturing firms' core processes (Kurkkio *et al.*, 2011; Lager and Frishammar, 2010). As the first contribution, the study has offered a nuanced characterization of novelty in radical innovations, complementing the manufacturing firm's own understanding with the additional perspectives of the equipment supplier and industry more generally. Different degrees of novelty in the RMTI reflect the extent of available knowledge and respective uncertainties in the industry, causing unique demands for the manufacturing firms' technology development and acquisition task. Thereby, the study responds to a previous call for better innovation categorization systems (Lager, 2002) and complements studies that have focused only on the adopter's perspective (Milewski *et al.*, 2015; Frambach and Schillewaert, 2002) or the industry level (Reichstein and Salter, 2006).

Second, this study has contributed by revealing the patterns of activities used for RMTI creation at the level of the RMTI project, across a variety of RMTI projects. The categorization of procurement-type, development-type and invention-type RMTI and their connection with the type of novelty offers a useful foundation not just for structuring forthcoming research, but also for designing processes and support routines for companies' practice. Previous research on RMTI creation processes has focused on firm-level practices, examining RMTI along with incremental development in limited empirical settings (Kurkkio *et al.*, 2011; Rönnberg-Sjödin, 2013). We complemented the previous case studies by covering a larger number of RMTI projects and promoting a contingency view for using appropriate RMTI processes for the respective level of novelty in the RMTI project, taking into account the novelty for both the manufacturing firm and the equipment supplier, and the industry more broadly.

Third, the findings contribute by revealing the role of manufacturing firms as active creators of RMTI and collaborators in RMTI processes in addition to their previously acknowledged role as adopters and implementers of RMTI. Manufacturing firms contribute as initiators, sponsors and active participants in the technology and process development work and are thereby necessary partners for equipment suppliers. We found that the collaborative activity increased with increased novelty of the RMTI and when moving toward invention processes, and thereby offered contributions toward open innovation research (Huizingh, 2011; Van Lancker *et al.*, 2016; West and Bogers, 2014). The results extend empirical research on radical innovations, particularly by enriching the understanding of manufacturing technology innovation processes.

6.2 Implications for practice

This study has several implications for practice. First, the descriptions of phases in the RMTI creation process provide a framework for planning RMTI projects and help in developing established processes for RMTI. Second, the findings showed that different types of RMTI creation processes are needed depending on the novelty levels of the RMTI. Rather than establishing generic and broad processes and systems for manufacturing innovation and development, the findings support a differentiated approach toward establishing processes and systems that best support the different types of RMTI. The proposed categorization framework for separating the low/medium/high-level novelty projects provides practical guidelines for establishing the differentiated processes.

Third, when planning RMTI processes, firms can be strategic regarding the roles and activities within and between them and the partner firms. For manufacturing firms, determining the needed technical support from the equipment supplier firm can help in selecting the most appropriate equipment supplier and in identifying the most appropriate phase for their involvement. For equipment supplier firms, negotiating and planning for the appropriate resources and time required for allowing the learning related to the first-time experience has strategic implications for the success of the firms. They must understand their different roles in the process, depending on the novelty of the RMTI. The approaches used in this study to map the activities and roles may be useful as a framework for targeting the efforts of the partners involved in the RMTI project.

6.3 Limitations and further research

The data collection method involved retrospective interviews, which include the risk of important facts being forgotten or misinterpreted (Eisenhardt and Graebner, 2007). To improve the validity and comparability, the companies were consistently advised to propose successful and recent RMTI projects and to focus on the knowledgeable informants involved in the RMTI projects with first-hand knowledge. The data on RMTI processes related to activities and stages were obtained from interviews with just one, or in some cases, two to three persons per company. Therefore, there is a limitation related to the depth of knowledge and data per company; however, due to the sampling strategy used, data could be collected for multiple RMTI projects and industrial contexts instead of only a few projects in a specific context. The study thereby complements previous research and serves as a broad pre-study, allowing for a broad mapping of the types of RMTI and RMTI processes across industrial, organizational and technological boundaries. Further studies are encouraged to combine the interview-based findings with such data as patents, industry articles and suppliers' post-innovation technology sales data, to develop further knowledge on suppliers' actual achievements with the RMTI.

The findings support the accumulation of knowledge on RMTI creation processes from different industries, against the dominant approach of studying processes within either assembled products industries or process industries only. The results pave way toward developing a theoretical model on novelty and RMTI processes, and testing it with a broader sample of RMTI projects, potentially involving also unsuccessful RMTI projects. The findings support an integrative, open innovation view toward RMTI creation processes, and future research should examine the different actors' roles more broadly, as RMTI creation typically requires the active involvement of both manufacturing firms and technology suppliers. This would enrich current research, which has been limited to investigating RMTI processes as product development for equipment supplier firms or adoption-implementation for manufacturing firms. This would also expand the research of open innovation to process innovations that require organization-specific knowledge and may cause a challenge to involving external partners (Huizingh, 2011). Because other organizations were involved in invention-type RMTI process, further research could explore the roles of research institutions and other technology partners as additional actors for an integrated view of RMTI creation process.

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Appendix 1

Project	RMTI name	Technology shift involved	Time
1	Anti-tarnish coating on silver	Chemical bath → ALD coating technology equipment	2000–2009
2	3D printing of casting dies	Creating wax mold for casting by pressure-injection equipment using rubber dies → direct 3D printing of wax mold for casting	1997–2012
3	Industrial particle coater based on nano-technology	CVD, PVD coatings → ALD coating technology	2006–2010
4	Continuous deposition process for thin-films	0 → new process enabling industrial application of thin-film coatings in continuous production environment	2005–2009
5	Flexible automation of testing tool	Manual testing→ rigid automated testing equipment → flexible equipment	2000–2005–2014
6	Automation of large furnace	Manual and smaller → automated and large furnace process line	2000–2010
7	New process for lignin extraction as side stream in wood pulp manufacture	0 → new process and equipment technology	1990–2015
8	Implementation of new assembly process for electronic device manufacture	Old → new assembly technology (interviewee regards names as confidential)	2013–2015
9	New concept for heating web in paper manufacture	Old heat roll → calendaring roll technology	2010–2015
10	Automation of stacking process in transformer core manufacture	Manual stacking of sheets in core → automated stacking	2008–2013
11	Automation of large engine head assembly	Manual operations → automation of process steps (e.g. testing) and robotization	2007–2010
12	Cheaper cutting tool for slots on circumference of motor plates	high volume equipment available only → create a low volume tool with innovative engineering	2014–2015
13	Automation of spot welding process for round plates in motor	Manual welding→ automated, robotized welding; holding tool redesign (big impact)	2006–2014
14	Paper pulp making technology	Process using traditional catalyst → modified equipment and process for using new catalyst	1990s–2013
15	Energy plant to utilize production plant by-product as renewable fuel	0 → new process equipment to enable use of less homogeneous fuel	2013–2014
16	Automation of production plant	Manual operations → robotized	1995–2009
17	Automation of production plant	Plasma cutting → laser cutting with automation; manual welding → robotized welding	2001–2014
18	New technology in manufacture of specialized silicon wafer	Interviewee considered names of technologies as confidential	2013–2016
19	3D laser technology sheet metal cutting equipment	Punching machine → 3D 6-axis laser cutting technology equipment	2000–2001
20	Special-purpose equipment: joining machine for large pipe flanges	Old tools → tailored joining equipment	2010–2012
21	Special-purpose equipment: insulation machine for generator coils	Manual insulation winding → semi-automatic equipment	1996–2002–2006
22	Special-purpose equipment: Inductive-heating based semi-automatic joining machine for generator coils	Manual gas soldering equipment → semi-automated induction heating equipment	2007–2009
23	Novel technology equipment for electronics component manufacture	Wet etching technology → dry etching technology	2005–2011

Table AI. Description of the 23 RMTI projects

Appendix 2. Interview outline

(1) Introductions and background:
- Introduction of interviewer and interviewee.
- Company background and information.
- Existing systems, processes, practices in the firm for radical vs incremental development in production.
- Overview of an example of radical change in production technology in the firm and how it was implemented:
  - What does the technology deal with?
  - What is its role in the manufacturing system of the firm?
  - How was it discovered and implemented (background, start, activities, end and current state)?
- Further discussion on the above example, with help of the following questions.

(2) Emergence of the new process/equipment idea:
- What was the key driving factor for the emergence of the idea?
- Was the new technology well-established at the time? Extent of uncertainty that it would work well for the intended application?
- Were there many competing ideas at the time when this idea emerged?
- What was the role of the equipment supplier – motivator and driver vs technical expertise and support provider vs something else?
- Comments on the timing of the technology adoption with respect to competitors or general industry level.
- Special role, if any, of an individual, team, event or other factors in triggering the emergence of the idea for changing the production technology.
- Was the decision making for adopting a novel technology smooth and fast? Any turning points?

(3) Creation of the new process/equipment:
- Key activities.
- What was the scope of work, creation responsibilities at the manufacturing firm, equipment supplier firm, other partners?
- What was the composition of the project team in different stages – who did what?
- Extent of inventive effort, work done for creation of the needed equipment, e.g., how similar or different was the new equipment compared to previous equipment made by the equipment supplier firm, before this project.

(4) Implementation of the new process/equipment into production:
- How did it happen – was it an easy journey to make a change in the way of production?
- Did it involve significant experimentation and piloting during the installation and commissioning stage?
- Comments on competence destroying impact, e.g., were there any layoffs, old assets removed, new training, new personnel?
- Outcome: is the new technology now in smooth, routine operation?

- Were the desired benefits achieved? Were there any unexpected benefits or challenges after implementation?
- What was the role of customers and their feedback in the overall process for implementation?
- Any comments on critical enablers and barriers for this change, e.g., technical specialists, visionary leader, any resources?

(5) Closing:

- Any additions regarding the example project.
- Upon need, discussion on another radical innovation project (if available), in line with the above questions.
- Comments on the importance of ongoing minor changes in production equipment vs major changes in equipment technology for the firm.

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PUBLICATION
III

Suppliers' Technological Newness: Source of Uncertainty in Manufacturing Technology Innovations

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Suppliers' technological newness: Source of uncertainty in manufacturing technology innovations

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Abstract: Radical manufacturing technology innovations involve the introduction of a new technology in a firm's core production process. They require significant learning and knowledge transfer between the technology supplier and the technology introducing manufacturing firm. This study explores the technological newness for equipment supplier firms and linked technology uncertainties in high-novelty manufacturing technology innovation projects which feature technological newness not only for the technology introducing manufacturing firm but also for the equipment supplier firm. The findings reveal a four-dimensional construct for equipment suppliers' technological newness and linked technological uncertainties emerging in the manufacturing firm's innovation process. The findings pave the way for better planning and preparation for addressing technological uncertainties and linked inefficiencies in high-novelty manufacturing technology innovation projects. Implications for research on knowledge transfer for innovation are discussed.

Keywords: Technological uncertainty; technology newness; radical innovation; manufacturing technology.

1 Introduction

Radical manufacturing technology innovations (RMTIs) involve the design and introduction of a new technology in a manufacturing firm's core production system and require manufacturing firms' proactive innovation effort (Reichstein and Salter, 2006). RMTIs present challenges for manufacturing firms due to technology newness, as unknown technologies may be slow to develop and adopt. RMTIs may imply technology newness also for the equipment supplier firm, for the industry, and even at the level of the world (Reichstein and Salter, 2006). Technology newness introduces uncertainty about the tasks involved in the innovation process (Eslami and Melander, 2019), due to incomplete information required for completing the tasks (Rönnberg-Sjödin et al., 2016; Rösiö and Bruch, 2018; Stock and Tatikonda, 2004). Technological uncertainty is considered to have a significant influence on the budget and schedule performance in RMTI projects (Rönnberg-Sjödin et al., 2016; Stock and Tatikonda, 2004; Tyre and

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Hauptman, 1992). Further research is therefore needed to improve the efficiency and performance of RMTI projects under technological uncertainty (Rönnberg-Sjödin et al., 2016).

Previous research has studied technology newness for manufacturing firms (Barnett and Clark, 1996; Tyre and Hauptman, 1992) and related technological uncertainty in RMTI projects. RMTI is often treated as a technology adoption issue for the manufacturing firms that may face barriers to technology adoption. Knowledge and capability gaps may exist in the manufacturing firms concerning the new production technology, and this may create challenges in technology adoption decision making (Martinsuo and Luomaranta, 2018), and specifying requirements for equipment engineering (Rösiö and Bruch, 2018), and requires extra efforts for achieving the full benefits desired from the technology innovation (Bourke and Roper, 2016). Manufacturing firms need strategies and practices to manage technology uncertainty related to their technology newness (Rönnberg-Sjödin et al., 2016; Simms et al., 2021, Stock and Tatikonda, 2004; Tyre and Hauptman, 1992).

Manufacturing firms, however, are not alone in implementing the RMTIs, but they need external partners in such projects. Equipment supplier firms are important partners in RMTI projects (Rönnberg-Sjödin et al., 2016), either selling their existing equipment or innovating completely new technologies and processes. High-novelty RMTIs may involve technology newness also for the equipment supplier firm (Rönnberg-Sjödin et al., 2016). If equipment suppliers are only innovating and learning to design a radically new technology, this is likely to be reflected on the experiences of the manufacturing firm investing in RMTI, too. Technology newness for equipment supplier firms as part of RMTI projects has not been well understood. Overall, high-novelty RMTI projects have been under-investigated, and there are calls for further research on their unique challenges due to high technology uncertainty and the requirements for their successful management (Simms et al., 2021).

The purpose of this study is to explore equipment suppliers' technological newness as part of manufacturing firms' RMTI projects. The goal is to map the manifestations of equipment supplier firms' technological newness as a distinct source of uncertainty in RMTI projects. The study offers new knowledge on the managerial requirements stemming from technological uncertainty in the interplay of equipment suppliers (i.e., contractors) and manufacturing firms renewing their core production systems (i.e., customers) in RMTI projects. The study answers the following two research questions:

RQ1. What comprises technological newness for equipment supplier firms involved in RMTI projects?

RQ2. How do manufacturers experience uncertainty attributed to the technological newness of equipment supplier firms?

To tackle the exploratory research objective, this study adopted a qualitative exploratory research approach. Data on 16 RMTI projects involving newness for both manufacturing and equipment supplier firms were analysed for identifying what was new to equipment supplier firms and its linked technological uncertainties experienced as part of the RMTI creation process. The findings reveal a four-dimensional construct for equipment suppliers' technological newness and linked technological uncertainties. Implications for further research on RMTI projects and knowledge transfer for innovation are discussed.

2 Literature review

RMTIs: background

Manufacturing firms introduce new manufacturing technologies in their core production systems to expand their product portfolio and increase efficiency and quality (Milewski et al., 2015). In this paper, we use the term radical manufacturing technology innovation (RMTI) to refer to processes that manufacturing firms use to introduce a new technology in their core production system. RMTIs concern technology innovations in the core production system, and exclude other enabling operations in manufacturing plants, supply chain processes, and support systems. RMTIs involve new-to-manufacturing firm technology, whereas high-novelty RMTIs may be new also for the industry and the world (Chaoji and Martinsuo, 2019; Reichstein and Salter, 2006).

When manufacturing firms introduce new technology, they often set up a project for new technology equipment procurement, development, and implementation (Stock and Tatikonda, 2008). Equipment supplier firms are important partners providing the technology and equipment in these projects (Stock and Tatikonda, 2004). Low-novelty RMTI projects involve the procurement of ready and proven equipment solutions from the supplier firm, whereas high-novelty RMTI projects require joint development of new equipment (Chaoji and Martinsuo, 2019; Sjödin et al., 2016). The overall RMTI project consists of three broad phases: front-end, where the innovation idea and concepts emerge, partners are identified and a development project is initiated; development phase, where the detailed equipment and technology solutions are engineered, constructed and tested before being sent to the manufacturing site for installation; and start-up phase which involves installation and trial runs, followed by ramp-up of production using the new technology (Milewski et al., 2015; Stock and Tatikonda, 2004).

RMTIs, like other radical technology innovations, can be seen as a knowledge quest and creation process within the firm's networks (Hall and Martin, 2005). Due to technology newness for the manufacturing firm, these projects involve uncertainty and challenges regarding feasibility, performance, and integration with other technologies in the production system (Brown, 2001; Martinsuo and Luomaranta, 2018). Technological uncertainty is among key features of these projects. Reducing and mitigating the technological uncertainty and its linked difficulties are necessary in managing them (Simms et al., 2021; Stock and Tatikonda, 2004).

Technological newness and uncertainty in RMTIs

Uncertainty refers to insufficient information, understanding or knowledge for doing the task (Eslami and Melander, 2019; Simms et al., 2021). Technological uncertainty in RMTI relates to difficulties faced in introducing new technological knowledge in the firm's core production system, and such difficulties stem partly from technological newness and the firm's lack of knowledge and previous experience with the technology (Simms et al., 2021; Stock and Tatikonda, 2004).

Manufacturing firm's technological newness comprises of their lack of previous experience with the technology and degree of its dissimilarity from their previous technologies in terms of skill base and organizing principles (Stock and Tatikonda, 2004; Tyre and Hauptman, 1992). Manufacturing firms may face difficulties in technology

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evaluation and decision making in the project front-end (Martinsuo and Luomaranta, 2018) and understanding and communicating requirements to equipment supplier firms for designing and developing the new equipment (Rösiö and Bruch, 2018). When implementing the RMTI projects, manufacturing firms need to accumulate experience and transfer knowledge among the personnel to enable an efficient ramp up of production and initial use of the new technology, and to fully utilize the technology in their production (Brown, 2001). Deficient knowledge transfer at any phase of the RMTI project will lead to delays and budget overruns. Therefore, managing technological uncertainty is central for improving the efficiency of RMTI projects (Sjödin et al., 2016).

Technological uncertainty will require mitigating practices in the RMTI projects, for example, in terms of learning and knowledge transfer to the manufacturing firm, particularly from the equipment supplier firms (Linder and Sperber, 2019; Simms et al., 2021). Useful practices include gathering of information from preliminary trials, collecting inputs from the production team, and learning from suppliers prior to actual technology implementation (Simms et al., 2021). Also, geographical proximity and close relationship with equipment supplier firms may enhance the efficiency and effectiveness of knowledge transfer and manufacturing firm's RMTI project (Linder and Sperber, 2019).

Manufacturing firms will need understanding, targeted planning, and management of such knowledge problems in high-novelty RMTIs (Simms et al. 2021; Sjödin et al., 2016). High-novelty RMTIs with their extreme technological uncertainty are accompanied with other knowledge problems related to complexity, ambiguity, and equivocality due to lack of ready technology solutions and novelty present also for equipment supplier firms (Simms et al., 2021; Sjödin et al., 2016). Existing studies on technological uncertainty in high-novelty RMTIs are few, and there is need for further research on the management of uncertainty and other knowledge problems in different types of RMTI projects (Simms et al., 2021).

While technology newness and uncertainty in RMTI projects have been consistently connected in previous research (Simms et al., 2021; Stock and Tatikonda, 2004; Tyre and Hauptman, 1992), technology newness has been considered mainly from the viewpoint of the manufacturing firms as technology adopters. Despite the equipment supplier firms' centrality in RMTI projects, their experience of technology newness as part of RMTI projects has not been covered sufficiently before. There is a need to consider how equipment supplier firms' technology newness is reflected in manufacturing firm's technology introduction projects and related uncertainties.

3 Research method

We explore equipment suppliers' technological newness as part of high-novelty RMTI projects. This study followed a qualitative research strategy which is suitable for exploratory research seeking understanding on previously less understood phenomenon (Bryman, 2012).

A broad search was initially made for collecting diverse examples of RMTI projects, involving the introduction of a new technology in core production system at a manufacturing firm. We contacted production directors and managers in firms in Finland to enquire about their recent RMTI experiences and identified some RMTI projects for data collection. We also searched for information on the internet for manufacturing firms that had been active in introducing contemporary novel manufacturing technologies such as 3D printing and nanotechnology and found contact for some examples of RMTIs this way, too. Altogether, the search resulted in 23 examples of RMTI from diverse companies, such as ship building, pulp and paper manufacture, machinery manufacture, luxury goods manufacture etc.

From the total sample, 17 projects involved technological newness also for the equipment supplier firms and were initially selected for this research, following a purposive strategy (Bryman, 2012) where the selection criterion is the presence of the phenomenon of research interest. Data on one project was later deemed insufficient, and hence it was excluded from the analyses. Table 1 summarizes the 16 high-novelty RMTI projects analysed as part of this study.

Table 1 Data Collection

Project	*Project Description*	*Interviewees*
A	Thin film coating on silver luxury goods	Production Director, Manufacturing firm; Production foreman, Manufacturing firm; Vice President, Business unit, Supplier firm
B	Industrial particle coater based on nanotechnology	Vice President, Business unit, Supplier firm
C	Continuous-process equipment for thin-film coating	Vice President, Business unit, Supplier firm
D	Flexible/ multi-product testing tool	Head of Supply Chain Engineering, Manufacturing firm
E	Automation of a large furnace	Plant Manager, Manufacturing firm
F	New process for new side stream product extraction	Head of Innovation, Manufacturing firm
G	New equipment technology for paper web-heating	Production Director, Supplier firm
H	Automated pressure testing of a very large assembly	Production Development Manager, Manufacturing firm
I	Small-batch compatible slot cutting tool	Manufacturing Unit Manager, Manufacturing firm
J	Automated welding of ribs on large motor plates	Manufacturing Unit Manager, Manufacturing firm
K	Large-scale implementation of a chemical process	Vice President, Production, Manufacturing firm
L	Process equipment for using novel renewable fuel	Vice President, Production, Manufacturing firm
M	New technology in the manufacture of a material	Sr. Process development engineer, Manufacturing firm
N	Joining equipment for large pipe flanges	Business Director, Supplier firm
O	Insulation machine for coating large coils	Business Director, Supplier firm
P	Joining machine for making large coils	Sr. Production Development Manager, Manufacturing firm

The data for each RMTI project was collected through semi-structured interviews with key informants involved in the RMTI projects. The interviewees were typically production development managers or senior managers who had directed or participated closely in the RMTI project. For all the projects, we requested for further interviews with other closely involved persons and access to project documentation for enabling richer data and information on the projects. These were realized for some projects. The interviews followed a thematic outline which was consistently used across the interviews to allow for similar kind of information on all projects. The outline enquired information on the events, activities, actors, and also key enablers and challenges through all the phases of RMTI projects. The interviews typically lasted about an hour. All interviews were conducted in company premises in conference rooms and were recorded with the permission of the interviewees.

We also searched publicly available information on the studied projects for additional information and triangulation of the data. To validate the findings, we presented a summary from the data and its preliminary analyses to the interviewees. A results workshop was conducted and also other managers in addition to the interviewees were invited.

A qualitative abductive approach was used for data analysis. The initial reading of the interview transcripts pointed at the relevance of equipment suppliers' technology newness to the RMTI project experiences of managers. For example, manager in project L mentioned, "*...we have problems, and it's due to this technology and the equipment suppliers not having much experience in that area*". This prompted our interest in exploring what is new to equipment supplier firms participating in these projects and focusing on the linked difficulties and uncertainties in the RMTI projects. An open coding approach was followed, for studying both the equipment suppliers' technological newness and the uncertainties experienced in the projects linked with lack of knowledge and ready solutions at equipment supplier firm.

The initial codes were refined by comparing the codes with each other and matching them across the data from all the projects. In this way, four distinct categories of technological newness to equipment supplier firms in RMTI projects were obtained: context, application, construction and technology newness. The linked uncertainties and difficulties experienced in the projects also reflected these four themes. At this stage, we searched for previous literature on technological newness and uncertainty in RMTI projects (e.g., Barnett and Clark, 1996), and in other than RMTI literature (e.g., Hong and Hartley, 2011). However, existing frameworks were unsuitable and did not provide direction for further analyses.

4 Findings

Equipment suppliers' technological newness in RMTI projects

The studied projects varied in what exactly was new in the solution development from the equipment supplier firm's perspective. Analyses of the data for aspects in the RMTI project that presented unfamiliarity or first-time experience for the equipment supplier firm revealed four primary dimensions of technological newness: Context, Application, Construction and Technology.

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The manufacturing firm's specific context, such as its core product and product-mix, layout and production system, and other surrounding processes in the manufacturing plant, was new to equipment supplier firms in projects A, B, C, E, H, J, M, N and P. For example, in project A, the equipment supplier firm was not familiar to the intricacies of luxury goods making process: "*There are lots of different things we do to the pieces before they go to the coating machine, and they [equipment supplier firm] don't know how that thing goes*".

In some projects, the kind of technology use involved in the RMTI project was new and presented many unknowns for the equipment supplier firm. Application newness involved application of the technology for unique or different materials, forms, volumes, and scale of production or new levels of operating requirements and conditions such as accuracy level, temperatures which generated higher-level generic requirements that need to be understood in order to make the technology application feasible. For example, as the equipment supplier firm manager in project B elaborated: "*We were in an area or unexplored area of process beyond the process window we used to be at…".*

In projects C, E, F, G, I, L, O, and P, the actual build of the equipment presented newness and first-time experience for the equipment supplier, for example in the type of structure, size, and scale of the equipment. In project E, the manager from manufacturing firm shared: "*The supplier didn't have so much experience with equipment of this size*".

Technology involved in RMTI projects F, G, L, and O was new for the equipment supplier firm. In Project O, it was a first-time experience for the equipment supplier to develop equipment utilizing the new automation featuring technology, and the technology itself was developed during the project in projects F, G, and L. Thus, technology newness concerned a lack of full understanding of the technology and engineering industrial equipment utilizing it for the equipment supplier firm.

The above four types of newness for the equipment supplier firms in RMTI projects are connected with each other, and yet emphasize distinct aspects related to the project. For example, where the technology itself presented newness and first-time experience for the equipment supplier firm, application newness followed. However, for some projects, the application of technology to such kind of novel circumstance (large scale, very different form and shape of material to be coated) was the main novelty to the equipment supplier, while they had expertise in the technology and thus no technology newness. The projects varied in the number of dimensions that were new for the equipment supplier. Also, within projects with similar type of newness, such as context newness for the supplier firm, the degree of newness varied based on whether the project involved significant unknowns about developing the solution or whether the kind of development work was also unfamiliar and presented a first-time experience for the supplier firm.

Technological uncertainties in RMTI projects

The studied high novelty RMTI projects involved technological uncertainty and related difficulties. The projects faced a lack of clarity on the needed technology equipment, and the interviewees linked some of the difficulties with a lack of ready solution and full knowledge needed for it at the equipment supplier firm. For example, a manager in manufacturing firm in project L noted, "*Now, if we look backward, this process is operating well, but in this drying process, we have problems, and it's due to this technology and the equipment suppliers not having much experience in that area*". Similar comments were noted in other projects, and this prompted the analysis of difficulties linked with the lack of knowledge and experience at the equipment supplier firms. The issues dealt with the equipment suppliers' lack of knowledge related to the context, application, construction and technology involved in the RMTI project. Table 2 summarizes the range of uncertainty experiences across the phases of studied RMTI projects.

In project A, B, C, E, H, J, M, N and P, there was lack of clarity on context-related requirements to be captured in the concept of the equipment. This was linked with uncertainties and difficulties experienced during the different phases of the project. For example, in project P, the manager explained linked difficulties in the designing phase: "*When the supplier was finalizing the machine, we started to express some needs for additional functions to the machine… during the trials we find some new challenges there, the machine supplier needs to fix those*". The other projects involved similar delay and rework related to context requirements uncertainty and linked difficulties. For example, equipment supplier manager in project C noted: "*There were again some new things identified [at the start-up phase] that needed to be re-built. They wanted something different eventually.*".

Application requirements were unclear in projects A, B, C, E, F, H, I, K, L, M. This created uncertainty at the front-end of these projects related to the application feasibility and performance. For example, manager in Project K described: "*And actually, one risk was that can we operate the digester in that way, or were there problems in the digester process so that the stability is not so good?*". Similar uncertainty in the front end and development phase for project B were noted by manager in supplier firm: "*We were not sure how long was the time of diffusion we needed to allow and the kind of mechanical tumbling the particles, and the coated particles especially, can tolerate"*. The uncertainty and linked effort and difficulties were reflected in the delays and long period of time and rework in these projects.

Projects C, D, E, F, I, L, P involved uncertainty on the details of the design and construction of the equipment at the project front-end. Linked difficulties in the development of the equipment consisted of trial and error, and during start-up included parts and components not working properly. For example, the equipment supplier firm manager in project C noted, "*There was a big vacuum chamber...that was in a crucial role in making the real hardware work* [during development phase]. *There were long tests with that. Some re-work around that design*". For project E, the manager at the manufacturing firm noted difficulties in the start-up phase: "*For example, when we started to heat them up into the right temperature, we saw that there were lots of distortions in the inner parts of the furnaces. And they* [supplier firm] *had to make some changes in the design and changes for the structures, also here on site*."

Technology feasibility and performance uncertainty was present in projects where the technology was developed as part of project or was unproven (F, G, L), and where the technology was a first-time experience for the supplier (O). Linked difficulties were experienced in the design and engineering work using the technology. For example, manager in project L shared "*There was the technology problem there that how we can infeed the material to this belt so that, it is very stable in every part."*

Table 2 reveals the range of uncertainty experienced in manufacturing firms, following from technology newness to the equipment suppliers throughout the phases of the RMTI projects. The four types of uncertainty were consistently present across the project phases and, thereby, characterized the project's dominant uncertainty. The findings suggest that equipment suppliers' technology newness on one or more of the

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four dimensions may explain the nature of knowledge gaps experienced by the technology-adopting manufacturing firm in the project.

Table 2 Technological uncertainties experienced across the RMTI project

Type of uncertainty	*Front end*	*Development*	*Start-up*
Context-related requirements	- Lack of clarity on context-related requirements - Lack of clarity on ideas for fitting the technology to the context - Feasibility and performance uncertainty	- Lack of clarity on context-related requirements and related difficulty in identifying requirements and accommodating them in late design phase	- Additional user requirements and/or context requirements are spotted
Application-related requirements	- Lack of clarity on application-related requirements - Technology bottlenecks - Feasibility and performance uncertainty	- Lack of clarity on technological requirements and related difficulties in making technology work and perform (e.g., trial and error in designing)	- Additional technology application requirements are spotted
Construction-related requirements and performance	- Lack of clarity on details of the full equipment solution - Construction feasibility and performance uncertainty	- Difficulties in designing the details and assembly and in making the construction (e.g., trial and error, re-work)	- Equipment does not work and/or perform as desired. Gaps in the construction design need to be resolved.
Technology requirements and performance	- Technology feasibility and performance uncertainty	- Difficulties in making technology work and perform (e.g., trial and error in designing)	- Technology in the equipment does not work and/or perform as desired. Gaps in the design need to be resolved.

5 Discussion and conclusion

This study drew attention to technological newness for the equipment supplier as a source of uncertainty in high-novelty RMTI projects. The study reveals a four-dimensional construct of technological newness for equipment supplier firms and reports how the newness appears across the studied RMTI projects. Manufacturing firms, in turn, experience analogous technological uncertainties stemming from the lack of knowledge and lack of previous experiences. As key result, the study reveals the diversity of informants' experiences of equipment supplier's technological newness throughout the life cycle of high-novelty RMTI projects.

Contribution

This study makes two key contributions to previous research literature on RMTIs: first, we present a project level perspective on knowledge transfer for RMTIs, against the previous firm level knowledge transfer models for RMTIs (e.g., Linder and Sperber, 2019). Second, the study contributes to previous knowledge on sources of technological uncertainty in RMTI project (e.g., Simms et al., 2021), by adding understanding on equipment suppliers' technological newness as a potential source of uncertainty in high-novelty RMTIs.

The findings highlight the need for a comprehensive project-level analysis of knowledge gaps and needed learning as part of the RMTI project, including the knowledge needs of the equipment supplier. For the manufacturing firm, this means also preparing to support the supplier firm in their knowledge accumulation needs, as it may contribute to reducing technological uncertainty experiences in the project and impact the performance of the manufacturing firm's RMTI project. Previous research on knowledge transfer for RMTIs emphasizes the importance of knowledge inflows from equipment supplier firm to manufacturing firm (Linder and Sperber, 2019). We argue that in high-novelty RMTI projects knowledge is accumulated also at the equipment supplier firm and within the project (equipment and solution that is jointly being built).

We contribute a four-dimensional framework on equipment supplier's technological newness. The findings, thereby, offer deeper understanding on the sources of difficulties in RMTI projects. Previous research on the management of technological uncertainty in RMTI projects consistently links technological newness to technological uncertainty (Simms et al., 2021; Stock and Tatikonda, 2004; Tyre and Hauptman, 1992). While technological newness for the manufacturing firm has been well understood (Barnett and Clark, 1996; Stock and Tatikonda, 2004; Tyre and Hauptman, 1992), this study complements such research by revealing the technological newness of equipment supplier firm as a source of manufacturing firm's uncertainty as part of high-novelty RMTIs.

The results show evidence of the presence of uncertainty over the life cycle of RMTI projects. The manufacturers' experience of uncertainty was sustained, to some degree, across the RMTI project phases, from front-end and development to start-up. This extends previous understanding on technological uncertainty in RMTIs from cross-sectional studies mainly investigating uncertainty in a specific project phase (Rönnberg-Sjödin et al., 2016; Simms et al., 2021) and reveals the continuity and evolution of uncertainty over the project life cycle. The exploratory research design mapping similarities and differences in technology uncertainty experiences across various high-novelty RMTI projects complements previous in-depth investigations of a few selected contexts (Simms et al., 2021).

Practical Implications

For managers and industrial practitioners, the findings have implications for identification and planning for technology uncertainties in high-novelty RMTI projects. The findings provide insights into equipment supplier's technological newness as part of high-novelty RMTI projects. Understanding supplier firm's technological newness and its links with difficulties faced in manufacturing firms' RMTI projects is useful for manufacturing firm managers managing high-novelty RMTI projects, as it may explain problems and failures of technology implementation.

The findings urge manufacturing firms to take a broad look at the knowledge accumulation needs as part of high-novelty RMTI projects, to include also the knowledge accumulation needs of equipment supplier firm. Thereby, a comprehensive project level rather than firm level assessment and planning of needs for knowledge transfer and accumulation in the project will enable planning for uncertainties involved in high-novelty RMTIs. Clearer understanding of equipment supplier’s knowledge gaps can enable manufacturing firms to proactively support them in their knowledge accumulation, thereby impacting the performance of manufacturing firm’s RMTI project.

The findings have implications also for supplier evaluation and selection as part of high-novelty RMTI projects. Manufacturing firms’ RMTI project will experience uncertainties linked with equipment suppliers’ degree and type of technology newness. The four-dimensional construct offers a fine-grained understanding on areas where to enquire and probe for supplier’s previous experience and preparedness for the project. This can open up new ways of identifying appropriate equipment supplier for high-novelty RMTI project, compared to the ordinary supplier search, for example, based on long relationship or cost bidding.

Limitations and further research

The exploratory research design enabled capturing broad patterns in equipment suppliers’ technology newness and linked technological uncertainties in a wide variety of RMTI projects, but the research design is limited in the depth with which every individual RMTI project was studied. There are some validity limitations to consider regarding the cross-sectional single-informant data collection for many projects and the accuracy and completeness of the respondents’ accounts. Various efforts were taken to ensure the validity of the findings, including the informants’ close involvement with and understanding of the project, viewing of related documents, such as presentations, where possible, a search for publicly available reports and articles on the project to triangulate the data, and testing of tentative findings by presenting them to informants in a results workshop. Deeper involvement through multiple informants and longer visibility for the project (e.g., through in-depth case studies) would result in richer project data. The exploratory research design, however, enabled the mapping of patterns of technological uncertainty in different projects and contexts. In this way, the study complements previous in-depth investigations of a few selected contexts and answers the call for a wider scope investigation (Simms et al., 2021).

The findings from this study encourage further investigation of suppliers’ and manufacturers’ task division and collaboration in high-novelty RMTI projects. The study calls for attention to project level needs for knowledge accumulation, besides firm level models for knowledge transfer for radical innovation. This research paves the way for future studies on increased efficiency in implementing RMTI projects. Further research could connect the degree of technological newness for supplier firms with assessments of efficiency and manufacturers’ activities of problem solving in RMTI projects. Identifying the knowledge and capability gaps in high-novelty RMTI projects will assist further in the agenda of making RMTI projects and processes more efficient (Linder and Sperber, 2019; Rönnberg-Sjödin et al., 2016; Simms et al., 2021).

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PUBLICATION
IV

Managers' Search Practices at the Front End of Radical Manufacturing Technology Innovations

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RESEARCH ARTICLE

Managers' search practices at the front end of radical manufacturing technology innovations

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Managers of manufacturing firms have important tasks in choosing novel technology solutions for the firm's production process. The emergence of ideas for radical manufacturing technology innovations and managers' proactive search for radical ideas and concepts for developing production processes have not been well understood. This study concentrates on managers' search practices at the front end of radical manufacturing technology innovations. We analyzed managers' practices in the early phase of nine radical manufacturing technology innovation projects across three firms. Radical manufacturing technology innovations require acknowledging both process innovations for the manufacturer and product innovations for the equipment supplier. The findings of this study revealed alternative patterns regarding the use of directed and autonomous search processes, internal and external information sources and open and closed supplier searches. This study offers new knowledge on the nature of the information processing task that managers face and on the search practices that managers use at the front end of radical manufacturing technology innovations. The study contributes by differentiating the managers' search practices based on the specific innovation scope in terms of the technology, equipment and production concept. Propositions are offered concerning the drivers and use of managers' search practices at the front end of radical manufacturing technology innovations.

KEYWORDS
front end, idea and concept development, information search, manufacturing technology, practices, radical innovation

1 | INTRODUCTION

Manufacturing firms introduce new technologies in their production processes to enable the manufacture of next-generation products or dramatically enhance the performance of current products (Milewski et al., 2015; Simms et al., 2021). Radical manufacturing technology innovations (RMTIs) imply that the technologies are new to the product manufacturer, and they may potentially be new for the equipment suppliers and the world, too (Chaoji & Martinsuo, 2019). RMTIs, thereby, involve high uncertainty and complexity (Simms et al., 2021), represent a demanding information processing task (Kleinschmidt et al., 2010) and require skilled management. Introduction of new manufacturing technology in a firm's core production processes calls for significant investments in technology equipment, causes disruptions to existing production routines and may require adaptations to existing operations, new skills and capabilities to fully integrate and enable benefits from the new technology (Brown, 2001; Martinsuo & Luomaranta, 2018; Milewski et al., 2015). The failure to introduce the needed technologies in production in a timely manner poses threats to business profitability and survival (Sinha & Noble, 2008). Despite their business criticality and management challenges, previous knowledge on the management of RMTI projects in manufacturing firms is sparse and further research has been called for (Kurkkio et al., 2011; Rönnberg-Sjödin et al., 2016; Simms et al., 2021).

This study concentrates on the RMTI front end, that is, the early phases of RMTI projects, where the emergence of RMTI ideas remains weakly understood (Linder & Sperber, 2019). The decision to invest in RMTIs is a strategic decision, requiring various investigations and consideration of alternative solutions at the front end of innovation. The front end of RMTIs can be considered a fuzzy phase, where personnel search for and process information and evaluate, develop and screen ideas that they can eventually propose for investment (Simms et al., 2021), leading to setting up a RMTI project for developing, procuring and installing novel technologies and processes for production (Frishammar et al., 2013, 2016). Generally, the typical front-end processes in RMTIs are already well known (Frishammar et al., 2013; Kurkkio et al., 2011; Milewski et al., 2015; Simms et al., 2021), but the processes whereby the ideas for RMTI emerge and the role of manufacturing firms and equipment suppliers in them remain unclear (Linder & Sperber, 2019).

In this study, we treat the front end of RMTI as a manufacturing firm's information processing task involving high degrees of uncertainty (Galbraith, 1977; Tushman & Nadler, 1978) and requiring integration of information both within the manufacturing firm and from external suppliers. Previous research on the emergence of radical innovation ideas highlights information search and processing by individuals and teams, resulting in novel combinations of knowledge (Acar & van den Ende, 2016; Aloini et al., 2013; Bessant et al., 2010; Nicholas et al., 2013, 2015). Equipment suppliers are key partners at the front end of these innovations (Chaoji & Martinsuo, 2019; Reichstein & Salter, 2006; Rönnberg-Sjödin et al., 2016).

This research is motivated by two major knowledge gaps in extant research. First, the manufacturing firms' perspective on ideas emerging at the RMTI front end remains unclear and requires further research. Equipment suppliers are often considered in a central role as sources of new manufacturing technology (Reichstein & Salter, 2006), and also consulting firms may bring in novel ideas (Frishammar et al., 2016; Kalogerakis et al., 2010). However, manufacturing firms as technology users play an important role in generating ideas for radical process innovations (Linder & Sperber, 2019), through their access to firm-specific process knowledge that is not easily available to outsiders. The work in the development and implementation of novel technology equipment clearly requires collaboration between the manufacturing firms (as technology users) and equipment suppliers (as technology providers) (Rönnberg-Sjödin et al., 2016), and the manufacturer's process knowledge is crucial for the ideas. There is a need to understand how ideas for RMTIs emerge within manufacturing firms that invest in their future production capacity and capability.

Second, there is a need to understand what happens in practice among the managers involved in RMTI initiation, that is, how managers participate in the information search for RMTI ideas. Although new product development tends to start from identifying a market opportunity (Kim & Wilemon, 2002), the need for manufacturing innovations may emerge within the firm's internal processes from problems in efficiency, functionality or quality (Kurkkio et al., 2011). Radical innovation ideas emerge in the problem-solving activities of individuals and teams, through various processes of analysis and information search (Frishammar et al., 2016; Reid & de Brentani, 2004). Managers' effort to search for relevant information is necessary to discover the right idea and develop the solution concept (Acar & Van den Ende, 2016; Frishammar et al., 2016; Reid & De Brentani, 2004). The emergence of radical innovation ideas is often understood as adhoc results of exceptional, unique circumstances and motivated individuals (Pihlajamaa, 2017; Reid & de Brentani, 2004; Rice et al., 2001). Managers are in key roles by bringing in possibilities for discontinuous innovations and structuring relevant information prior to decision making (De Brentani & Reid, 2012; Gemünden et al., 2007; Reid & De Brentani, 2004). Although previous research points at the key role of managers in the emergence of radical ideas, the search practices of managers in manufacturing firms at the front end of RMTI remain less understood and need further research (Simms et al., 2021).

The goal of this study is to obtain new knowledge on managers' practices in idea and concept development in manufacturing firms that renew their technology base. The main research question is: *What kinds of search practices do managers in manufacturing firms use for new ideas at the front end of RMTI?* The study contributes to the literature on the front end of radical innovations by characterizing the information processing task specific to the front end of RMTI and by offering empirical evidence on managers' information search in handling that task successfully. More specifically, the study 1) reveals the scope and nature of RMTI ideas from the manufacturing firm's perspective and, thereby, informs on its information processing task (complementing, e.g., Kleinschmidt et al., 2010); 2) characterizes patterns of managers' information search practices stemming from the amalgamation of process innovations for the manufacturer and product innovations for the equipment supplier (responding to explicit needs, e.g., by Simms et al., 2021); and 3) shows evidence of the task division and its underlying reasons between top and middle managers in the RMTI front end (offering nuanced information, e.g., in relation to Linder & Sperber, 2019).

We next introduce RMTIs, their early phase tasks and previous research on managers' practices at the innovation front end. Then a nested multiple-case study is introduced, covering nine RMTI projects in three firms. The findings revealed the multi-dimensionality of the RMTI concept scope, four different information search tactics and two supplier search tactics of managers. Finally, we discuss these findings considering previous knowledge and develop five propositions concerning managers' search practices and factors differentiating them at the front end of RMTIs. Implications for further research and practice are discussed in this study.

2 | LITERATURE REVIEW

2.1 | Radical manufacturing technology innovations

Firms pursue radical innovations to create new capabilities, find and serve new customers and markets and enhance their competitive position. Radical innovations imply the creation and use of novel technologies to grasp or create new market opportunities (Tushman & Nadler, 1986). Radical novelty can either take shape or be restrained already at the front end of innovations (Robbins & O'Gorman, 2015). Research concerning the front end of innovations has predominantly dealt with new product development, its idea search and commercially attractive product concepts that match customer needs (Eling & Herstatt, 2017; van den Ende et al., 2015). However, firms may create a significant shift in their business by innovating the technologies and processes that they use to manufacture their products (Frishammar et al., 2013; Kurkkio et al., 2011; Milewski et al., 2015; Simms et al., 2021). Some radical innovations may also be discontinuous, in that they open up a completely new trajectory compared to what the firm is used to (Bessant et al., 2010). This study concentrates on the front end of RMTIs.

RMTIs enable firms to revise their product portfolios more dramatically than with just one product innovation. They may occur through creating or acquiring new industrial equipment (Milewski et al., 2015; Reichstein & Salter, 2006) or implementing new production processes (Frishammar et al., 2013; Kurkkio et al., 2011; Simms et al., 2021). The invention, development and piloting of new technology-based solutions in production require the manufacturing firm to interact with external technology suppliers (Chaoji & Martinsuo, 2019).

A higher degree of technology novelty is reflected in higher uncertainty, higher information processing needs (Tushman & Nadler, 1978) and a more complex process at the front end of such innovations (Chaoji & Martinsuo, 2019). In the simplest cases, the product, that is, the required equipment and technology are ready and available from an equipment supplier firm. Then, the front end of RMTIs merely requires a pre-study for designing the process and investment planning by the manufacturing firm (Rönnberg-Sjödin, 2013). The manufacturer can decide the investment based on competing offers from alternate suppliers and commercial negotiations that clarify the features of the suppliers' solution (Rönnberg-Sjödin, 2013). High-novelty RMTIs, in turn, represent newness also for the equipment supplier firms. Both the technology-based equipment and the process are new for the manufacturer and the supplier. There may be no ready, proven solutions known in the industry or also in the world (Chaoji & Martinsuo, 2019; Reichstein & Salter, 2006). The front end of high-novelty RMTIs involves more unknowns, and a greater search and development effort is needed (Chaoji & Martinsuo, 2019; Rösiö & Bruch, 2018; Simms et al., 2021; Sjödin et al., 2016). The front end of high-novelty RMTIs has remained under-investigated, and managers' practices require further research (Simms et al., 2021).

2.2 | Front end of radical manufacturing technology innovations

Previous research on RMTI covers the process at the front end of innovation and reveals the phases, activities (Frishammar et al., 2013, 2016; Kurkkio et al., 2011) and nature of detailed information to be developed (Frishammar et al., 2013). The front end of product innovations tends to concentrate on ideas, customer needs, product concepts and market opportunity (Eling & Herstatt, 2017; Kim & Wilemon, 2002). In turn, the RMTI front end is more focused on strategic assessments (Frishammar et al., 2013), problem mapping, creation and solving (Frishammar et al., 2016) and solution exploration and planning (Frishammar et al., 2013). The front end of process technology innovations tends to be iterative and already features technology experimentation (Kurkkio et al., 2011). The knowledge problems at the front end create challenges for managers in deciding on the investment (Flores-Garcia et al., 2021; Martinsuo & Luomaranta, 2018; Simms et al., 2021).

The front end of both radical product and process innovations typically ends in a decision to start the actual development project, but the nature of the innovation differentiates the decision concerning the scope of the project. For product innovations, the front end typically ends in defining and selecting the product concept to be implemented in the project and setting up a project team (Kim & Wilemon, 2002; Kurkkio et al., 2011). In contrast, Kurkkio et al. (2011) show that the front end of process technology innovations also includes various tests and experiments, requiring direct work with the processes being developed. Besides a product definition of pieces of equipment, there is a need to achieve a sufficient process definition and plan for its implementation in the manufacturing firm, including awareness of alternative process technologies by competing suppliers (Frishammar et al., 2013). This implies significant financial investments into the technologies and process implementation work, both inside the firm and with partners (Bruch & Bellgran, 2012; Rönnberg-Sjödin, 2013). Therefore, the front end of RMTIs includes identifying the needed technology, defining the process, defining and selecting the technology solution concept and identifying the supplier with whom the details of the process will be developed. For high-novelty RMTIs, the front end additionally includes the development of the technology, process and equipment concepts needed for their implementation.

2.3 | Managers' search practices at the front end of radical innovations

RMTIs represent significant investments to the firm's future production capacity. They require managers' efforts in identifying the right process problem, scouting for alternative solutions and negotiating with suitable equipment suppliers. They represent a forward-looking search concerning the manufacturing firm's future production capacity and, therefore, require new information for the consideration of future courses of action (Jissink et al., 2019). The information processing view generally acknowledges that relevant information may be accessible both within the firm and among its external stakeholders (Kleinschmidt et al., 2010; Tushman & Nadler, 1978). Specifically, scanning of technological factors externally has been associated with innovation success (Frishammar & Hörte, 2005). Such studies, however, do not deal with RMTI or the front end of innovation specifically. Previous research on the front end of radical innovations has covered the search modes, search space and supplier search primarily for product-related innovations and only in limited ways for RMTIs, as summarized below.

Previous research identifies two main modes concerning the search of the core concept for radical innovations, which we refer to as directed and autonomous search. In directed search, the idea flows from the organization to the individuals, and it has also been referred to as a structured search process (Reid & De Brentani, 2004). In directed searches, top management sets a formal project and delegates information searches to technical managers (Reid & De Brentani, 2004). A study on radical sustainability-oriented product innovations revealed some organizational, strategy-driven heuristics that drive the search and emergence of radically novel ideas (Kennedy et al., 2017). According to empirical studies with process technologies, directed search and early phase strategic alignment may be needed for long-term process development projects due to their strategic nature (Frishammar et al., 2013; Kurkkio et al., 2011).

In autonomous search, the problems and ideas emerge among individuals who take the initiative to analyze the problem without initial top management input, referred to as an unstructured search process (Reid & De Brentani, 2004). Technical-level managers play a key role in generating radical innovation ideas due to their boundary-spanning position (Gemünden et al., 2007). High autonomy and working outside of organizational routines are typical to skunkworks projects that require certain human resource practices, as was shown in an automotive case study (Oltra et al., 2022). This understanding on how radical innovation ideas emerge is informative for the development of firm-level practices to encourage innovations (Bessant et al., 2010). For example, firm-level practices for recruitment and team-member selection can be developed for encouraging and supporting individual-level radical idea generation processes (Aagaard, 2017; Oltra et al., 2022; Pihlajamaa, 2017). Although Kurkkio et al. (2011) have mentioned the use of informal processes in short-term projects, the use of an autonomous search, specifically in RMTIs, is not visible in earlier empirical studies.

The search of new information during the front end of radical innovations is sometimes considered in terms of the search space (Lopez-Vega et al., 2016; Nicholas et al., 2013) or search strategy (Chiang & Hung, 2010; Terjesen & Patel, 2017), that is, where the firm searches for new information for the innovation. The search space often covers the external environment as a source of information, including markets, suppliers, competitors and research institutes. (Terjesen & Patel, 2017). The firms' market-oriented culture has been positively associated with radical product innovations (Naranjo-Valencia et al., 2017). Forward-looking external search has been positively associated with project innovativeness in a broad survey study of product innovations (Jissink et al., 2019). For radical product innovations, proactive exploration is needed and the search may be bounded to an existing cognitive frame or unbounded, seeking a new cognitive frame (Nicholas et al., 2013). A study on open product innovations differentiated between local search spaces that concern familiar technology fields and distant search spaces that concern previously unexplored domains (Lopez-Vega et al., 2016). A survey study across different manufacturing industries found a negative connection between search breadth (number of external information sources) and process innovation, and a positive connection between search depth (importance of the information sources) and process innovation (Terjesen & Patel, 2017). Collaborative open search is considered as particularly useful for discontinuous innovations that require out-of-the-box thinking (Wiener et al., 2020). Such examples emphasize external search but tend to consider either product innovations or process innovations.

The search space for RMTIs specifically requires the consideration of both product and process innovations and contextualizing the information appropriately to the manufacturing firm (Linder & Sperber, 2019). The survey study of Linder and Sperber (2019) on production process innovations found that *internal* knowledge sources are more influential for radical process innovations than external knowledge sources. They justify this through the contextual uniqueness and the necessity for the organization to implement profound changes in the processes (Linder & Sperber, 2019). Some studies, however, suggest that equipment suppliers are important external sources of new information for RMTIs, too, as they know the technologies (Reichstein & Salter, 2006; Rönnberg-Sjödin et al., 2016). Also, consulting firms have the experience to create novel ideas for radical manufacturing innovations (Frishammar et al., 2016; Kalogerakis et al., 2010). The manufacturer and supplier need to cooperate in information processing, to ensure early user involvement and joint problem solving for reducing uncertainties (Rönnberg-Sjödin et al., 2016) to serve the manufacturer's needs. More research has been requested on the contextual conditions of manufacturer–supplier relationships and related information transfer (Linder & Sperber, 2019) and the manufacturing firm's perspective on developing RMTI ideas and concepts (Frishammar et al., 2016).

External suppliers are not only used as sources of information at the front end of RMTI but also their involvement is needed in defining the equipment and process concept, prior to the top management's investment decision. The supplier search, therefore, has to occur at the RMTI front end. The study by Chaoji and Martinsuo (2019) showed that manufacturers seeking high-novelty RMTIs included the suppliers earlier in the front end, due to the novelty of the technology for the suppliers and the need for inventions. Manufacturers cooperate with equipment suppliers to explore and then exploit the new technologies and competences in their processes and solve emerging problems (Gemünden et al., 2007; Rönnberg-Sjödin et al., 2016). However, they may find it difficult to commit to one supplier immediately, as they need flexibility in resolving technological, commercial and organizational uncertainties (Melander & Tell, 2014). Manufacturers may be tempted to use their existing technology partners for

TABLE 1 Characteristics of companies and interview data

	Firm A	Firm B	Firm C
Range of firm sizes (revenue MEUR)	>100 MEUR	>1 BEUR	>2 BEUR
Size	Small (<500 employees)	Medium (about 1000 employees, part of a larger corporation)	Large (about 5000 employees, part of a larger corporation)
Industry	High-tech raw material industry	Process industry	Assembled products industry
Market position	Niche market leader, among top 10 global firms	Market leader, among top global firms	Market leader, among top global firms
Number of interviewees	5	7	5
Job positions of interviewees (examples)	Process engineering manager, Sr. VP products and Sr. process engineer	Sr. VP production, Sr. VP business development, project manager and plant manager	Production development manager, manufacturing manager and Sr. R&D engineer
Average duration of interviews	> 60 mins per interviewee (total duration: 413 minutes)	> 60 mins per interviewee (total duration: 504 minutes)	> 60 mins per interviewee (total duration: 416 minutes)

their RMTI, but some studies indicate that familiar suppliers with known technologies may primarily support incremental innovations to existing technologies (Linder & Sperber, 2019). In turn, a large gap between the supplier's new technology and the target application would enable high-novelty ideas (Linder & Sperber, 2019). A collaborative foresight study showed that technological complementarity is particularly helpful for the partners to learn from each other, but some extent of similarity and nearness is needed, to find common understanding and shared language (Gattringer et al., 2017). The study by Terjesen and Patel (2017) on search breadth versus depth indicates that in-depth cooperation with selected partners is more relevant for process innovations than the number of partners. The previous studies tend to take an organizational view of supplier search, whereas the managers' practices in exploring supplier alternatives as part of the RMTI front end remain less clear.

3 | RESEARCH METHOD

3.1 | Research design and cases

We conducted a multiple-case study on the front end of nine RMTI projects in three manufacturing firms. Multiple-case studies enable the comparison of the focal phenomenon across different empirical cases, to understand core patterns in how the phenomenon unfolds and to discover theoretical explanations (Thomas, 2011). The firms were identified from a set of 17 manufacturing firms in a preceding study on RMTIs. As RMTIs are rare in firms and management of innovations is context dependent, we specifically sought for firms that had implemented multiple RMTI projects in recent years, to enable both within-firm (different RMTI projects) and cross-firm comparisons (the firms' overall RMTI approach). We also sought for clearly different firms in terms of size, type of technology and manufacturing and industry, to account for contextual variety. The three firms thus selected included a semiconductor manufacturing firm (Firm A), a process-based manufacturing firm (Firm B) and an assembly manufacturing firm (Firm C). The three firms are among market leaders and well recognized in their industry. Table 1 provides more information on the three firms.

We decided to investigate specific RMTI projects in each firm, to capture an in-depth view of the firms' RMTI approach, to access accurate information on practices (i.e., what managers actually do) and also to enable within-firm comparison, thereby taking a nested case-study approach (Thomas, 2011). Three RMTI projects were studied as nested cases within each firm. The projects represent the context for managers' search practices at the RMTI front end and enable capturing a holistic understanding. Although each project is unique, as nested cases, the projects also followed the established processes and routines of the case firm. A summary of the nine projects is given in Table 2.

Three RMTI projects were selected with a key contact manager at every firm using three main criteria. First, the projects had to be recent, that is, completed within the past years or near completion so that they would enable access to knowledgeable informants still within the firm. Second, the project had to represent new technology equipment in the firm's core production processes, thereby making them strategic investments. Third, the innovation had to be radical, in terms of the introduction of a new-to-the-firm production method. Also, the innovations that had been completed were considered as successful in that the solutions were taken into use in production. The projects had been completed (implemented in production), with the exceptions of C-1 in the concept development phase and B-3 in the late implementation phase (installation). In the projects, access was possible to nearly all managers involved closely at the project front end. Exceptions were in Project B-2 (manager involved in detailed concept development unavailable), in Firms A and C projects (purchase manager unavailable) and in Firm C project (unavailable top managers). Equipment supplier firm managers were purposely excluded from the data collection because our interest was to capture the manufacturing firms' internal search practices. The projects in Firms A and C were implemented in the same manufacturing site, whereas in Firm B, two projects were implemented at the same

TABLE 2 Description of studied RMTI projects and interview data collection

Projects	Project description (new technology in core production process)	Number of interviewees
Firm A: Semiconductor manufacturing		
A-1: Alternate process technology needed for next-generation product	Introduce new technology that would enable higher accuracy in certain product features beyond those enabled with previous technology and tooling (needed for making next-generation product).	3
A-2: A better process and tool	Introduce new technology and tooling that would enable a neat finish on certain product features, compared to the present technology and tooling that left a crude finish (customers complained of imperfect finish).	2
A-3: Alternate process approach needed for next-generation product	Introduce a new process approach and linked tooling for generating higher performance semiconductor raw material (needed for making next-generation product).	2
Firm B: Process-based manufacturing		
B-1: A superior process approach	Introduce new chemical process and needed equipment for achieving the same product from raw materials with higher yield and quality (for meeting company's strategic production development targets).	5
B-2: Unique application spin	Introduce new processes (and related technology and equipment) for generating renewable fuel using unique biowaste side-streams to replace previous fossil fuel-based processes.	5
B-3: A breakthrough process idea	Introduce technology to recycle and reduce effluents released into the environment (for meeting company's strategic production development targets).	4
Firm C: Assembly manufacturing		
C-1: An attractive alternate process approach	Introduce alternate assembly approach (switch from cutting-and-joining to bending) and linked technology to improve process efficiency and quality.	4
C-2: A superior process approach	Introduce new process technology and related equipment for automating previous manual process.	1
C-3: A superior process approach	Introduce new tooling and technology to replace previous manual and slow process.	1

manufacturing site (B-1 and B-2), and one project was at a different site (B-3).

3.2 | Data collection

Data were collected from multiple sources on each firm's processes for the initiation of RMTI, including 17 semi-structured key informant interviews (Table 1), and internal documentation at the RMTI front end. Some interviewees had participated in more than one project, and all such projects were covered within a single interview meeting, each project separately (Table 2). Some interviewees were interviewed more than once on the same project, but these were not counted as separate interviews. The interviews were conducted on the company premises and were recorded with the permission of the interviewees. Three interviews were conducted via online meetings due to the distant locations of the interviewees.

Data collection for the individual projects involved semi-structured interviews with all closely involved persons at the front end of the project, to cover various perspectives and collect rich information. The data collection per project was thus limited to the front end of the project, until the point where the decision to give a contract to an equipment supplier was made.

The interview outline (Appendix 1) was developed based on experiences from a pre-study with a broader sample of firms, and the focus was on the front end of RMTI. It included questions on the timeframe, practices, events, people involved, search process, the evaluation and selection processes for the selected RMTI projects in which the interviewees had participated and the established processes and routines for the initiation of RMTI within the firm. The interviewees were allowed to give an uninterrupted account of the events and practices at the front end of the RMTI project, as they remembered. Further questions were asked to ensure comprehensive coverage of all topics and to delve deeper into issues that seemed central to idea emergence and concept development in each project.

Project documentation and firm documentation were shown and described during some interviews or shared after the interview. Information on some projects was sought through the internet, the company website and the equipment supplier's website. The supplementary documentation was used to enrich and triangulate the data.

3.3 | Data analysis

The data analyses followed an abductive approach (Dubois & Gadde, 2002), including sensitivity to the data and repeated interplay with previous literature on the front end of radical innovations generally and managers' practices in them specifically. During the initial reading of the data, the events and timeline of the RMTI front end of the projects were mapped to identify interesting events and recurring themes. A summary of the firm-specific overview was shared with the firms' contact person to get feedback and clarify any missing details.

Then, an open coding approach was targeted at the overall idea and concept development task and managers' related practices. During and after the open coding, we reflected on the data already present in literature, searching for support, for example, from Frishammar et al. (2016) on the centrality of the problem at the front end of radical innovations and Bessant et al. (2010) on engaging, enabling and experimenting practices in selecting discontinuous innovations. After the open coding, we formed a tentative picture of the idea and concept development task, featuring problem formulation, idea search (including technology, production and equipment idea) and process and equipment concept definitions. As this offers an understanding of the special nature of the RMTI front-end task compared to other types of radical innovations, we report these findings in Section 4.1 as background to the managers' search practices. To understand the patterns of these issues across projects, we used cross-tabulation of the coding, wrote short project narratives and sought similarities and differences across projects and firms. This phase led us to focus our attention on managers' search practices in more detail.

The analysis was then continued with pattern coding, in which we grouped detailed issues discovered during the earlier analysis into three clusters of search practices. Each project was carefully coded according to the information source, mode of information search and supplier search practices, each of which was grouped into two main categories. Again, during the coding, we returned to suitable literature, especially acknowledging the information search at the front end of radical innovations (see Section 2.3). Table 3 summarizes the main categories from the analysis, which were used for structuring the results in Sections 4.2–4.3. The analysis was concluded into a two-dimensional framework of four different information search practices during idea and preliminary concept development and two supplier search practices during concept development. Each project's dominant pattern concerning managers' practices was identified by using and refining the previously developed project narratives, in addition to the pattern coding.

4 | FINDINGS

4.1 | Scope of the front end of RMTI

The nine projects that were studied represented radical departures from existing methods, tools and technologies used in production, and the starting points and scopes of their concepts differed. The primary

TABLE 3 Pattern codes, their definitions and example quotes in the analysis

Main categories of analysis	Description	Example quotes
Information source		
Internal	The technology idea was known and emerged within the firm.	'*We did not have to survey the technology. We knew the technology. That was clear from old patents*'. (manager, A-3)
External	The technology idea was not known and it was sought from outside the firm.	'*The mission of that project was to identify which technologies we could introduce which would make. Two-micron tolerance realistic. So, it was basically a technology survey*'. (manager, A-1)
Mode of information search		
Directed search	Information search was initiated at the top manager level, delegated to lower organizational levels and followed established phases and routines.	'*It was, given to me to solve the problem*'. (manager, B-3)
Autonomous search	Information search was initiated and carried out at the middle-manager level, through their own initiative, in an informal manner and without pre-planned phases.	'*It was, actually it was kind of, the planning started along this other project. When we started these discussions (with the supplier) and we get these ideas*'. (manager, A-2)
Supplier search		
Open supplier search	No previous knowledge of suitable suppliers. Open and broad investigation of supplier and solution alternatives, before detailed concept and investment planning and negotiation.	'*This supplier which we chose we came into contact with through (our) old equipment which we have plenty, they had a supplier which discontinued production. But there was one key guy who then instructed us to contact this company...*' (manager, A-3)
Closed supplier search	Previous knowledge of preferred suppliers. Narrow and limited supplier and solution analysis and comparison merged with detailed concept and investment planning and negotiation.	'*We always go to these main suppliers and ask them what they, do they have this kind of process we had chosen*'. (manager, B-1)

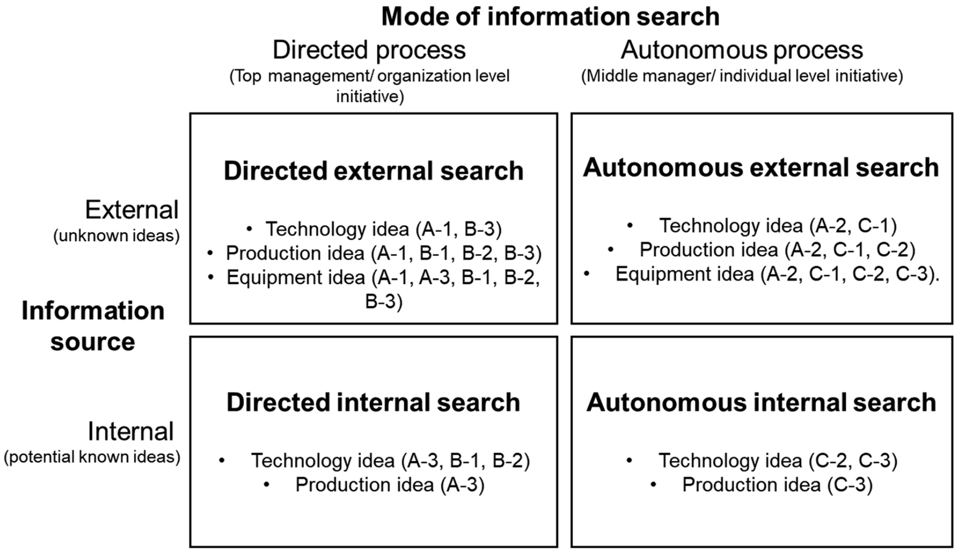

FIGURE 1 Four patterns of managers' information search practices at the front end of RMTI projects.

innovation *idea* featured a new type of production process and a new technology and targeted a specific problem. For projects A-1, A-3, B-1, B-2 and B-3, the process or technology problem drove investigations to identify a suitable technology. In projects A-2, C-1, C-2 and C-3, the idea for solving the problem emerged through an opportune event rather than as an output of planned investigations.

Three key ideas formed the full concept of RMTI, which were new technology, production idea and equipment idea. In some projects, a potential technology idea was identified already when the initial problem was noticed. Information collection and subsequent discussions on the technology followed, including a comprehensive assessment related to technology fit, feasibility, risks and benefits. This information search gave shape to specifying the production concept (i.e., process innovation for the manufacturer) and equipment concept (i.e., product innovation for potential suppliers). Detailed concept development was done for production (how to implement the aspired production utilizing the new technology) and equipment (what is the needed equipment and how to get it). In addition to the comprehensive concept description, investment planning required further information collection and market and supplier studies in cross-functional teams. The manufacturers needed to identify potential equipment suppliers, engage in deeper discussions with them and make requests for offers to potential suppliers.

4.2 | Information search practices in RMTI front end

The emergence of technology, production and equipment ideas differed to some extent across the projects. One or more of these three key ideas for every project was not evident at the beginning, and managers took action to search for and identify them. We identified four dominant patterns of search practices that managers used in information search at the RMTI front end, as shown in Figure 1.

4.2.1 | Directed external search

In many projects, idea and concept development started with a strategic production problem attracting top managers' attention. In some projects (such as A-1 and B-3), the problem was very holistic, requiring ideas for technology, production and equipment, whereas in other projects (such as A-3, B-1 and B-2), the technology need was more apparent, and only production and equipment ideas were needed. Top managers initiated formal investigations, installed cross-functional steering committees and activated information collection on markets, technologies and knowledge inside the organization.

The search and investigation were delegated to middle management. Middle managers led a team of experts from production, process development, R&D and other functions, possessing relevant information concerning the technology and the original problem. They initiated discussions with knowledgeable colleagues, encouraged broad Internet and literature searches, activated informal brainstorming and explored application solutions from existing and new supplier contacts. In project B-3, the manager mentioned, '*I asked them (supplier firm colleagues) what they have in their idea box*.' In addition, chance events or serendipity were perceived as useful in discovering information for idea creation. The interviewee in this same project, B-3, elaborated: *'the early discussion (at the supplier) was with that type* *of fellow who was working, as partly retired. If he had been totally retired, I don't know what in that case. It was very good luck in that way. Because there was only one fellow, remembering, what they have done, 16 years earlier [laughs]'*.

Once the technology idea was identified, managers and their expert teams pursued further information through literature searches, benchmarking visits to installations of similar equipment elsewhere, asking suppliers and/or making test pieces using the supplier's demonstration equipment. The information collected was used for developing a broad understanding of the production concept and equipment concept, as well as assessing the fit and feasibility of using the technology in the manufacturer's own production.

4.2.2 | Directed internal search

Also here, top managers initiated a discussion based on an identified technology problem, but attention was immediately directed at previously known technology alternatives. In projects B-1 and B-2, strategic production development process brought focus and attention to potential alternative production processes, whereas project A-3 started with a meeting of a middle manager and top manager to discuss the problem and clarify the technology idea. These projects, therefore, had slightly different paths for the technology idea compared to the production and equipment ideas that followed, as indicated in the directed external search.

Middle managers brought in technology ideas through their ongoing tasks, projects, interactions and knowledge on alternate technologies. The manager in project A-3 mentioned: *'Basically we have done quite much production scale research and development in this area. Of course, we have studied all the research or papers involved in this area. And we have, lucky to have, quite capable personnel to even have an idea what direction we have to take and what kind of tooling we would need to accomplish that particular task, to get this kind of product capability higher.'* Here, the information needed for the technology ideas was known to managers.

Once an idea was identified, the top manager(s) launched an investigation to develop the technology concept to understand whether and how to implement it. As part of this, middle managers investigated the selected idea, collected information and made assessments. In projects A-3, B-1 and B-2, the production idea and/or the equipment idea were unknown, and these projects followed directed external search practices.

4.2.3 | Autonomous external search

In some projects, the production problem was first identified and reacted to among middle managers, for example, in a production or product unit (A-2 and C-1), or as customer feedback and requests for developing product features (A-2). The operational problems were also linked with strategic goals and development plans. The managers did not have a technology, production or equipment idea to begin with. Instead, serendipity and opportune events occurred in middle managers' open discussions with suppliers on their inventions and other projects, their own equipment needs and visits to other manufacturing plants.

Middle managers had to deal with the problems in their daily operations, which motivated them to search for new technology ideas. In project C-1, a senior R&D engineer was dissatisfied with the present production method for a product, and this experienced problem encouraged him to search for a radically novel approach. Some managers mentioned their individual interest and disposition in finding ideas for better production processes. A manufacturing manager in projects C-2 and C-3 mentioned: *'It's my personality. I always try to think how to make these easier'*.

Compared to directed search, managers' discussions with suppliers were not necessarily driven by a specific problem. Rather, managers explored technologies openly and broadly, and this exploration led to an idea. In project A-2, a manager discussed with a supplier when ending a previous project with them, and he noticed equipment that could be a viable alternative for one of their problematic processes: *'When we were discussing and they were showing their development work, we saw this kind of picture [of a technology solution]. And it's really something similar that we are doing here. And that was the, where we got this idea … We were able to combine and start thinking that could we somehow use this kind of a process.'* Similarly, in project C-3, the production unit had a routine of visiting an equipment supplier of specialized machine tools, and the manufacturing manager came across prototype equipment that could function as a potential solution for their problematic operations.

The middle managers sought additional information to assess the feasibility of the technology and fit it with the production context. In project C-3, the manager selected a customer order where such equipment could be utilized, identified the requirements and ordered a prototype tool to assess whether and how it performed. In project A-2, the manager ordered test pieces with the supplier's equipment to assess the technology performance.

4.2.4 | Autonomous internal search

In two projects, managers experienced an important problem in their unit, and they already possessed knowledge of some technology directions that would resolve the problem. In projects C-2 and C-3, the technology idea was clear from the outset: they were well-known superior technologies in use for mass production (automation and press-tools). However, some ideas needed for concept development were unknown.

Top managers were not involved in these projects. Middle managers experienced the negative effects of the problem, attempted to solve them and discussed them in their unit. They promoted concept development by asking suppliers for their solution ideas (C-3) and devising ideas for the production concept (C-2). Although the technology idea was clear to begin with, concept development stalled temporarily when searching for implementation ideas.

4.3 | Supplier search practices in RMTI concept development

Moving to detailed concept development involved a greater commitment from the firm to the RMTI investment. In Firms A and B, the RMTIs required larger investments and continued with a directed process. Hence, top management decided on a concept planning project, established a cross-functional team and allocated a steering committee to monitor progress. In Firm C, middle managers developed the unit's investment proposals for top management, and they also led the detailed concept development, continuing with an autonomous process.

All projects required external supply for the manufacturing technology and process. To discover suitable alternatives, middle managers made inquiries and collected detailed offers from equipment suppliers. With suitable candidates, managers made accurate calculations and detailed production plans. Competing suppliers' alternate equipment concepts were compared, and commercial negotiations were initiated, especially in Firms A and B.

The RMTI projects differed from each other in the openness of the supplier search: three projects engaged in an open supplier search for the equipment solution, including a search for new suppliers, whereas six projects restricted their supplier and solution search to familiar main suppliers. The patterns were largely similar within each firm regarding open versus closed search for suppliers, and exception to the practice was linked with individual projects.

4.3.1 | Open supplier search

In projects A-1, A-3 and C-1, managers did not have definitive knowledge of potential equipment suppliers when they started the equipment and production concept development. The supplier search occurred through an open-ended inquiry among knowledgeable colleagues, consultants and familiar suppliers. Such an open-ended search was typical of Firm A due to its niche technology business and lack of dedicated suppliers. Managers and their teams made broad ongoing searches on the internet, participated in conferences and industry fairs and went to observe industrial equipment in other firms (e.g., customer firms) to identify alternatives. In project C-1, managers collaborated with a familiar equipment supplier during preliminary concept development, but they then realized the need for a specialized supplier for the new equipment and process and continued with an open supplier search.

Deep information was collected on the identified equipment suppliers and their plans for the needed equipment. For example, the investigating team in project A-3 included a friendly consultant who questioned the supplier's plans to find a better solution: '*he (the consultant) was kind of challenging the supplier's designs and calculations and expectations and material selections, if for no other reason than at least for the reason of making them make it double sure that they know what they are saying [laughter]*.' Similarly, in project A-1, a manager provided examples of many interactions with alternate suppliers. Supplier's expertise and willingness to develop the technology led to selecting one supplier and their solution, even if the supplier did not meet all assessment criteria during supplier comparisons and negotiations.

4.3.2 | Closed supplier search

After idea generation and preliminary concept development, managers of six projects (A-2, B-1, B-2, B-3, C-2 and C-3) had a clear idea of possible equipment suppliers. Closed supplier search was more typical to Firms B and C. Firm B had two main equipment suppliers with close knowledge of the manufacturer's production, and detailed offers were requested only from them. Firm C had close ties with some suppliers (machine tool designers and builders, robotics and automation specialist firms), appropriate for the type of equipment involved. Even if they did not have a detailed and complete understanding of the equipment and production concept (including technologies, requirements and needed adaptations for production), managers requested full solution offers from known suppliers who were also expected to cooperate with the manufacturing firm in solution development.

Managers in projects B-1 and B-3 collected deep information on equipment technology and plans of alternate suppliers, whereas managers in projects A-2 and B-2 did not have full information on the suppliers' plans for the equipment during concept development. They compared the offers and selected the most attractive offer and willing suppliers to continue negotiations for the solution development. For projects C-2 and C-3, there was only one credible equipment supplier, so the detailed concept development concentrated on equipment and process specifications and detailed investment planning.

5 | DISCUSSION

In this study, we investigated what kinds of search practices managers use in manufacturing firms at the front end of RMTIs when renewing their core production process, which is considered as a highly uncertain and demanding information processing task. The findings revealed the unique scope of RMTIs when the solutions are new not only for the manufacturer but also for the supplier: the developed concept must cover *both* process innovations for the manufacturing firm *and* product innovations for the equipment supplier firm. The analysis of nine RMTI front-end projects differentiated top and middle managers' practices across firms and projects. Below, we will discuss these issues along with some propositions for future research.

The study frames RMTIs as an amalgamation of the manufacturing firm's process innovation and the equipment supplier's product innovation, tied together with the novel technology. This result offers novel information on the nature of the information processing task faced by managers at the front end of RMTI, complementing studies on innovations more generally (Frishammar & Hörte, 2005; Kleinschmidt et al., 2010). Our findings highlighted three separate components within the RMTI idea, namely, technology, equipment and production, each requiring their respective information searches and analyses. Previous research has tended to concentrate on either a focal firm's key product idea needed for radical innovations offered on the market (Bessant et al., 2010; Reid & de Brentani, 2004) or the process problems of a firm driving the innovation in process technologies (Frishammar et al., 2013, 2016; Kurkkio et al., 2011). As process technology innovations are embedded in their organizational context (Milewski et al., 2015) and represent unknown technologies for the equipment supplier (Chaoji & Martinsuo, 2019), the technology study needs to be complemented with investigations of its use in the firm's specific production context. Therefore, the front end of RMTIs is portrayed as a more complex ground of information search, compared to product-centric radical innovations.

Proposition 1. RMTIs imply a combination of product innovations for the equipment supplier with process innovations for the manufacturing firm. The information search of manufacturing firms' managers will need to tackle both types of innovations and connect with suppliers already during the front end of RMTI, to provide a credible foundation for the investment decision.

Our findings showed that RMTIs emerge both based on strategic and operational grounds, and the starting point specifies the managers' mode of information search. The case firms differed in their use of autonomous versus directed search processes for RMTIs. Specifically, the directed searches started on strategic grounds, whereas the autonomous searches were initiated based on a production problem or customer feedback. The use of both search modes at the RMTI front end is in contrast to the assumption of mainly autonomous search processes at the front end of radical product innovations (De Brentani & Reid, 2012; Gemünden et al., 2007; Reid & De Brentani, 2004; Rice et al., 2001) and directed searches in process development projects (Frishammar et al., 2013; Kurkkio et al., 2011). Our findings demonstrate that firms may use both search approaches, depending on the circumstances.

Proposition 2. Strategic and operational needs define the mode of information search at the front end of RMTI. Top managers take a directive role in information search for RMTIs when the firm strategy includes ambitious goals for production, development and performance. Middle managers' autonomous search for RMTIs occurs based on operational performance problems and direct customer feedback.

The RMTI projects differ in their information search space, depending on unknown issues in the RMTI concept scope (technology, production and equipment) at the beginning. This deals directly with the combination of product and process innovations, demanding situation-specific equipment-related contextualization of information (Linder & Sperber, 2019). In manufacturing firms, process problems and related knowledge emerge inside the firm (Linder & Sperber, 2019), whereas a significant share of solution (i.e., equipment) ideas needs to be sought from external sources, equipment suppliers in particular (Reichstein & Salter, 2006; Rönnberg-Sjödin et al., 2016). Thus, our findings differentiate the information search space at the front end of RMTI based on the RMTI concept scope and related unknowns.

Proposition 3. The extent and type of unknowns in the RMTI scope specify the managers' search space. Managers rely on internal information first, to exploit ideas easily accessible. Managers initiate an external search, as a response to the unavailability of ideas and the need for breakthroughs.

The findings distinguished between the practices of top and middle managers, contributing to previous broad understanding of the practices of managers in the front end of RMTIs (Kurkkio et al., 2011; Simms et al., 2021). Top managers' active involvement was emphasized with strategic initiatives at the front end of RMTIs. This supports previous findings where top managers initiate external search investigations for strategic pressing needs (Kennedy et al., 2017). Middle managers not only acted on strategic tasks delegated by top managers but also engaged in autonomous searches to tackle local operational problems and propose investments to top managers. Middle and top managers' specific access to information flows and supplier relations defines their influence at the front end of RMTI.

Proposition 4. The division of work between top and middle managers at the front end of innovation is specified by the initial mode of information search. Directed searches initiated by top managers set requirements for middle managers' search efforts. Autonomous searches initiated among middle managers require top managers' approval, both for detailed concept development and investment decision. Middle managers are uniquely positioned to develop comprehensive insight on the entire RMTI concept, covering the technology, production and equipment and supplier alternatives.

Our findings revealed the early involvement of suppliers in RMTI concept development, dominance of closed supplier searches with known suppliers, purposive use of open supplier search for unknown technology niches and the interplay between the manufacturing firm and supplier in developing the process solution concept jointly. The search for suppliers and assessing suppliers' alternative equipment solution concepts appeared to be important in the detailed concept development to exploit the suppliers' knowledge and solve problems (Gemünden et al., 2007; Rönnberg-Sjödin et al., 2016) and, thereby, bring in the product (equipment) innovation to support the process innovation. Also, the collaboration during supplier search helped the supplier to become familiar with the manufacturer's unique process conditions, achieve benefits from complementary knowledge and develop common understanding and shared language, which resembles findings concerning collaborative foresight (Gattringer et al., 2017). The findings concerning open versus closed supplier search lend support to the importance of search depth in process innovations (Terjesen & Patel, 2017), whereas also suggesting that supplier familiarity does not necessarily hinder radical innovations (contrasting Linder & Sperber, 2019). Rather, the findings indicate that novel niche technologies without dedicated suppliers forced manufacturers towards an open search, due to suppliers being an additional unknown for the RMTI concept.

> **Proposition 5.** Manufacturing firms interact with equipment suppliers already during RMTI front end, both to identify alternative solutions and to help the suppliers familiarize themselves with the manufacturer's processes. Manufacturers use a closed supplier search to enable in-depth cooperation, reduce risks and benefit from previous knowledge. They will use open supplier search when the manufacturing technology niche is unknown, without dedicated suppliers, to collect rich knowledge on alternatives, test the suppliers' willingness to cooperate and build mutual commitment.

As an overall finding, this study brings together the amalgamation of product and process innovations, four patterns of managers' information search and supplier search and involvement as key features of manufacturing firm's RMTI concept development. These issues together clarify the nature of managerial work at the front end of RMTIs and assist in structuring its information search and assessment tasks. The focus on managers' practices offers a new viewpoint on the front end of RMTIs, complementing the problem-solving-centred (Frishammar et al., 2016; Simms et al., 2021) and activity-centred (Kurkkio et al., 2011) process models. Our portrayal of managers' practices in the RMTI front end, as anticipation of a strategic investment into future capabilities and capacities, opens up new possibilities, both through connecting RMTI with strategy, considering task allocation across organizational levels, and connecting the manufacturing firms with suppliers.

6 | CONCLUSIONS

This study exposes managers' search practices within manufacturing firms during the front end of RMTIs, answering calls for further research on the front end of radical process innovations (Frishammar et al., 2016; Simms et al., 2021) and complementing the company-level routines at the RMTI front end (Frishammar et al., 2013; Kurkkio et al., 2011). As the primary theoretical contribution, this study portrayed the RMTI front end as a complex, uncertain information processing task at the manufacturing firm (following Galbraith, 1977; Tushman & Nadler, 1978; Kleinschmidt et al., 2010), where previous research has pointed out the need for more knowledge on managing the RMTI front end (Rönnberg-Sjödin et al., 2016), clarifying the manufacturing firm's position (Linder & Sperber, 2019) and understanding managers' practices (Simms et al., 2021). Consequently, we offer new knowledge on the managers' information search in handling that task successfully in different manufacturing firms and different RMTI projects while cooperating with equipment suppliers. This study yielded three more detailed contributions.

First, we characterized the nature of the search for information at the RMTI front end and explained differences in the search practices by merging knowledge concerning radical product and process innovations. The findings, thereby, offer new information concerning the contextual conditions for managers' search practices, contributing to previous understanding on sources of radical process innovations (Linder & Sperber, 2019; Reichstein & Salter, 2006; Rönnberg-Sjödin et al., 2016). RMTI requires three different ideas to be developed into full concepts at the front end of RMTI: technology, equipment and production process. Each of these ideas and concepts may have its own search space, depending on the extent of unknown factors, as was shown in our findings. Research on product innovations tends to concentrate on the product only (Kurkkio et al., 2011; Reid & de Brentani, 2004), whereas process technology innovation research tends to handle process developments, not the product (Frishammar et al., 2013; Kurkkio et al., 2011). We showed that in the case of RMTIs there is a necessity to treat process innovation for the manufacturer and product innovation for the equipment supplier simultaneously, which connects two streams of research in a unique way.

Second, we revealed the scope and nature of managers' search practices in the early phases of RMTIs from a manufacturing firm's perspective. Managers were portrayed as active agents in renewing a firm's production processes through purposive information search, which adds to previous knowledge on practices at the front end of radical innovations (Bessant et al., 2010; Frishammar et al., 2016; Simms et al., 2021). Mapping the search practices according to the mode of information search, information source and supplier search revealed the nature of managers' search and characterized the front end of RMTI specifically. The idea source and problem type yielded project-specific patterns of information and supplier search, which adds to previous knowledge on the selection of managers' practices in the front end of radical and discontinuous innovation (Bessant et al., 2010).

Third, we offered new information on top and middle managers as active agents and task divisions between them at the front end of RMTIs. Top managers were involved in RMTI idea generation and solution decisions, and both directed and autonomous processes were used. This contradicts some previous findings on top managers' absence and use of autonomous processes in product-centric radical innovations (De Brentani & Reid, 2012; Gemünden et al., 2007; Reid & De Brentani, 2004; Rice et al., 2001) and directed searches in process development projects (Frishammar et al., 2013; Kurkkio et al., 2011). Our findings demonstrate that firms may use both search approaches and the top and middle managers' initial roles may vary, depending on the strategy, production performance problems and explicit customer needs driving the RMTI project.

As managerial implications, the study offers a framework that could be used to guide managers' information and supplier search practices at the front end of RMTIs. The framework acknowledges the starting points for RMTI in the manufacturing firm (strategic vs. operational), unique scope in the RMTI front end (technology, equipment and production concept) and necessity to involve the supplier early to learn the firm-specific processes. The search practices reported here, thereby, can help managers to see the alternative approaches for managing the front end of RMTI and stimulate actions in their own context. Both top and middle managers are active agents at the RMTI front end. Our findings encourage firms to enable both directed and autonomous routes for RMTI, to engage top managers into process development and empower middle managers to use their technical expertise in solving production performance problems. Our findings also encourage managers' openness towards opportune events during the information search, to enable discovery of radical, future-oriented ideas. Understanding of the equipment supplier's product innovation by the side of the manufacturer's own process innovation will help in planning for the RMTI project. Depending on technology familiarity and the expected degree of novelty, managers need to engage in open or closed supplier searches to commit equipment suppliers to the innovation project. Our findings suggest using information sources and modes of information search appropriate to the specific situation to develop the RMTI ideas into concepts.

Limitations are caused by the accuracy and comprehensiveness of the retrospective interview data. Further research and development are needed in broader and more versatile samples, to turn the propositions from this study into testable hypotheses. Although we delimited case selection purposely to RMTIs and sought variety in the projects, further research opportunities exist in comparing managers' practices across different RMTI project types and contexts. In this study, the focus was on individual managers' practices of information search. As the organizational context shapes the individuals' opportunity space and innovations may involve teamwork, the contextuality of managers' practices could be investigated further. This study did not cover the strategy alignment or discontinuity caused by RMTI projects, so further research could explore the strategy linkage of RMTI. Further research could assess the consequences of the various search practices and their fit to certain problems, types of RMTI ideas or contexts. Also, the division of tasks and coordination between top and middle managers in different RMTI projects will deserve further attention.

DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions.

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APPENDIX A: INTERVIEW OUTLINE

1. Introduction
   a. Overview of the purpose of the whole study, the interview and topics.
   b. Background of the interviewee: Could you describe your role, work in the firm and how you came to be involved in this project? Was this project exceptional compared to your other projects?
2. The initiation of the selected case example of radical manufacturing technology innovation
   a. Could you describe what happened in the early period of this project, before a contract was signed for its development with an equipment supplier firm?
      i. Timeframe
      ii. Who was involved and how?
      iii. Activities, phases, challenges, critical things and surprises
      iv. Trigger, beginning point and motives
      v. Search period: was there a search of any kind during this period? What was searched, by whom, why, how and alternative ideas?
      vi. When were equipment supplier firms contacted, and how were they identified? How different were their offerings, and how was the evaluation process?
      vii. Difficulties, challenges, for example, when there was no active work, no action taken on the idea, communication effort and difficulties in search and selection.
      viii. Critical things, for example, events, persons and practice seen as very important to successful idea emergence and development in this project.
      ix. Decision making and selection of idea and concept: how did this happen, any exceptions compared to normal decision making in such projects?
   b. Available documentation, for example, reports, plans, minutes of meetings and emails.
   If the interviewee was familiar with multiple projects, this section was repeated for other projects.
3. RMTI initiation processes in the firm
   a. Is there a common way, standard process or system that drives work on ideas involving newer technologies for use in production in this firm?
      i. Any department, any persons (special roles?) dedicated to following up on such options?
      ii. How about firm strategy and senior management? How do they promote, encourage and emphasize activities for exploring new processes and technologies in production?
      iii. How about the organization, for example, processes, systems and culture? How do they promote and support in some way or discourage such idea development?
4. RMTI initiation sources in the firm
   a. What are the main ways in which novel production technology ideas like this project come up?
      i. Network?
      ii. Suppliers?
      iii. Production inputs?
      iv. Sales/CRM inputs?
      v. Any other?
5. Closing
   a. Are there any other issues you would like to add?
   b. Next steps of the research
   c. Thank you