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## Abstract
Radical manufacturing technology innovations (RMTI) involve the introduction of new technologies in the firm's production processes. They represent especially challenging production investment decisions, due to inherent high risks and uncertainties. Firms' approaches to RMTI decision making are insufficiently understood. We explore the nature of RMTI decision making processes in nine RMTI projects from three manufacturing firms. The findings reveal slight differences compared to typical investment processes and organizations' different approaches for guiding the decision making.

**Keywords:** radical innovation, manufacturing technology, investment decision

### Introduction
Radical manufacturing technology innovations (RMTI) mean the development of the production process through a radical shift in the core production technology and related practices. They involve the introduction of new-to-the firm production equipment and enable big benefits such as targeting of new markets, creation of new products, and savings (Oke et al., 2007; Reichstein and Salter, 2006; Keupp and Gassmann, 2013; Maine et al., 2014). They require significant investments from the manufacturing firm and can be risky. This study deals with decision making concerning these risky innovative production investments.

The front end process for RMTI includes a search for alternative technologies and suppliers, idea selection, and further investigation to prepare a business case for enabling an informed decision for the investment (Frishammar et al., 2013). As compared to regular equipment investment proposals, decision making on RMTI investment proposals presents a greater challenge due to various risks and uncertainty. Radical innovations are not completely known and well understood in the beginning, and they will require learning and development during the innovation process (Von Hippel and Tyre, 1995). Existing literature does not comprehensively cover decision making in such a context: whether to invest in an RMTI proposal or not, and how to assess the investment options.

Manufacturing firms will face various dilemmas concerning the risks and potential benefits from the RMTI, and regarding the internal capabilities and external support available, during their decision making.

Therefore, the purpose of this paper is to explore manufacturing firms' practices in analyzing and deciding innovative production investments at the front end of RMTI. The main research question is: how do manufacturing firms evaluate and decide RMTI investment proposals? The focus is on radical innovations in the core production process, and incremental and peripheral innovations as well as product innovations are purposely excluded.

## Literature review

*Radical manufacturing technology innovations as risky production investments*

Radical technological innovations deal with the introduction of a technology that is radically novel and different from the previous technology it may be displacing (Harborne et al., 2007). Radical manufacturing technology innovations (RMTI) cover such innovations within the core production technology and process (Chaoji and Martinsuo, 2016, forthcoming). While discussion on advanced manufacturing technologies typically focuses on the technological innovation itself, RMTI imply changes more broadly including the supply, delivery and manufacturing processes and related ways of working. For example, change from subtractive to additive manufacturing could be considered as RMTI. RMTI do not cover innovations in non-core or peripheral production processes such as production quality control and monitoring (Bessant, 1982), or innovations in other than manufacturing operations such as material purchase processes (Parikh and Joshi, 2005).

Radicalness implies novelty at the level of the adopting manufacturing firm, and in some cases the novelty may be true also for the equipment supplier firm and the industry more broadly (Chaoji and Martinsuo, forthcoming). RMTI may require using non proven equipment and technologies, and therefore have greater uncertainty than other types of innovations. The overall creation process (development and implementation) for RMTI starts with activities related to idea search, selection and refinement (Kurkkio et al., 2011). Following the decision to invest in the development of the actual production equipment and its technology, the back end process involves the detailed engineering, construction, installation and production trials (Lager and Frishammar, 2010). A recent study has mapped the different types of RMTI processes and reveals differences based on the degree of novelty particularly at the front end of RMTI (Chaoji & Martinsuo, forthcoming).

The focus in this paper is on the decision making concerning RMTI as risky production investments at the front end of the innovation. Due to their centrality as part of the firm's production process, RMTI investments can be considered as strategic and long-term oriented. The objective of the front end of innovation is to reduce uncertainties and unknowns about the RMTI idea to enable 'informed' decision making (Frishammar et al., 2013). However, some extent of unknowns are present at the decision making as the innovation is not completely known and well understood until its pilot implementation as part of the project itself.

*Decision making in operations management*

Decision making involves the identification and selection from alternative options, and research on decision making suggests various pathways to choosing among alternative options and their potential impacts (Cook et al., 2007). Decision making can be structured, formal comparison and analysis of the alternatives using, e.g., multiple criteria decision

analysis methods (e.g. Ting, 2008). Also, it may be intuitive, unstructured and based on a person's experiences without systematic analyses of all alternatives (Tello et al., 2010; Kammerlander and Ganter, 2015). Furthermore, decision making in an industrial context is influenced by organizational processes and contexts, raising questions regarding the role of individuals making decisions versus organizational procedures and contexts influencing their decision making (Tello et al., 2010; Leiblein et al., 2002).

Accordingly, decision making can be perceived as a rational process involving the consideration of all possible alternatives, or it can be considered as boundedly rational where individuals consider such alternatives that are practically feasible (Turpin and Marais, 2004), leading to the selection of one possible best option. Research acknowledges that decision making is a behavioural process, wherein the outcome is considered to be linked with the individual involved, for example their previous experiences, values etc. (Evans et al., 2013). Within studies from the behavioural paradigm, the political view observes decision making as a social process of interactions between individuals from different interest groups, each group trying to maximize their gains and interests from the decision (Turpin and Marais, 2004).

*Decision making on RMTI investments*

There has been considerable research on decision making on selection of advanced manufacturing technologies, and both rational and behavioural paradigms have been covered. A large number of studies have concentrated on decision making support formulae and systems (e.g. Sambasivarao and Deshmukh, 1997; Chan et al., 2006; Osman and Cengiz, 2005). The dominant view perceives decision making on RMTI investment proposals to be a rational team-level decision making process comprising three stages: 1. Search for alternatives, 2. Screening alternatives and collecting facts, and 3. Comparing the alternatives in a team, to prioritize them and choose the best alternative (Baines, 2004; Farooq and O'Brien, 2010; Ordoobadi, 2012).

Manufacturing investment decisions are considered as challenging due to the presence of multiple criteria that need to be optimized in selecting the best technology (e.g. Chan et al., 2006; Iakymenko et al., 2016). In addition to economic criteria, strategic needs and risks have been shown to be important attributes in making the decision to invest (e.g. Chan et al., 2006; Iakymenko et al., 2016; Meredith and Hill, 1987; Farooq and O'Brien, 2010; Kakati, 1997; Stading et al., 2001). Some studies also highlight the role of previous experiences, intuitions in such decision making (e.g. Evans et al., 2013), and have described the challenges related to conflicts in interest groups in multi-department or cross-functional teams involved in investment planning teams (e.g. Ordoobadi, 2012; Choudhury et al., 2006; Lefley, 2018).

## Research method

A multiple embedded case study has been conducted to identify how RMTI investment proposals are evaluated and decided in practice. The selected three manufacturing firms are active innovators: they have had multiple successful RMTI projects in the past 15 years. The companies are from different industries and portray differences in their strategies for RMTI. Within each firm, three RMTI projects were discussed, totalling 9 projects. 17 expert interviews (totaling 27 hours of recorded interview data) were held with managers involved in the evaluation and decision making processes, covering nine different RMTI projects, three in each firm. Table 1 includes background information on the companies, their RMTI projects, and the interview data.

*Table 1 – Characteristics of companies, RMTI projects in them, and interview data.*

| | Firm A | Firm B | Firm C |
|---|---|---|---|
| **Range of firm sizes (in turnover MEUR)** | >50 MEUR | >1 BEUR | >2 BEUR |
| **Size** | Small (<500 employees) | Medium (about 1000 employees, part of a larger corporation) | Large (>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 |
| **Nr. of interviewees** | 5 | 7 | 5 |
| **RMTI projects covered in the analysis** | A1: New tolerance<br>A2: Feature replacement<br>A3: Higher performance | B1: Novel process<br>B2: Energy alternative<br>B3: Waste reduction | C1: Novel approach<br>C2: Automation<br>C3: Speeding up |
| **Job positions of interviewees (examples)** | Sr. Process Engineer; Process engineering manager, Sr. VP, Products | Sr. VP, Production; Sr. VP. Business Development; Plant Manager; Project Manager | Production Systems Development Manager; Sr. R&D Engineer; Manufacturing Manager |
| **Total duration of recorded interview data** | 467 min (approx. 8 hours) | 562 min (approx. 9 hours) | 580 min (approx. 9 hours) |

The interview outline included questions on timeframe, activities, events, people involved, search process, evaluation and selection process in the early period of the RMTI project before the investment decision was made. The interviewees were selected by key informants of the projects, due to their participation in the innovation front end. Interviews were arranged in meeting rooms in company premises, were recorded and transcribed. Separate interviews were arranged with all participants. Promise regarding confidentiality of information regarding names of firms, interviewees and the technology involved or product specific information was given.

We analyze what was known and unknown concerning the RMTI project and the business environment, and what were the key factors for decision makers generally in the firm's decision making. Also we explore the exceptions concerning the specific RMTI project, compared to regular investment decisions. We analyzed the data for the nature of the decision making process, including its activities, the use of systematic and formal practices versus intuitive and unstructured practices. The data was coded to identify the role of individuals, organizational processes, risks inherent in RMTI investment proposals and the key justification criteria and motivations for the decision. The projects were the unit of analysis, and observations were compared across the 9 projects to arrive at the findings.

## Results

*RMTI decision making process: Deciding on the technology and implementation concept*
Typical decision making on investment involves: 1. Search for alternatives, 2. Screening them and collecting facts, 3. Comparing alternatives in the team and deciding. According to the interviewees, RMTI decision making goes through these three stages, but actually covers two choices in a sequence: technology choice and implementation concept choice.

Typically, there are no known technology alternatives to an existing process for RMTI. The search for technology alternatives appeared in the interviews often as an ongoing long period when the managers engaged in discussions about the need to find an alternate technology or process. Some interviewees told about specific small exploratory projects as part of the search, to assess or test any potential technologies. In project A1, the firm made a decision to start a technology survey project to find an alternate technology. Typically, during this long ongoing period of active interest in finding alternate technology, the technology choice became clear. This involved either conclusive validation tests, sample pieces made (e.g. projects A1, A2), or depth of technical expertise that was accumulated during ongoing technological research. Typically, there was often one technology that was clearly selected for further investigation, and one of the reasons for this was lack of any other potential fit. For example, an interviewee explained the technology selection at the end of technology survey project in project A1 as follows: "*reasons for the selection were, well quite simple. First of all some of the processes were not capable so they were easy to drop out. Some were horribly expensive, so by order of magnitude too expensive or too low in capacity to be realistically useful. So we had basically two realistic options. And then the manufacturer of that one tool gave us the very clear message that they're not going to sell tool outside Japan. So that left us with one technology!*". Similar clear selection of one potential technology was visible in other projects too. For example, an interviewee explained about project B3: "*I think every second year in our company has been some kind of, small studies done how to handle these questions. But in those cases (this idea) has never raised up. ….it was only possible way to handle it. And Mr. (project head) was very eager, to make those studies to final end and then he was very happy that okay now we can handle this, biggest problem what (industry name) mill ever have had*".

Once a technology idea was obtained, the firms began to investigate this specific technology and gather data to understand its fit and feasibility to their unique needs. This largely included a search for possible suppliers and gathering information about their equipment concepts and implementation concepts for the technology in the firm's process. The facts regarding implementation ideas gathered through implementation plans from suppliers and discussions with suppliers, their previous experiences with the technology and existing industrial users of the technology were then typically evaluated by internal technical experts for evaluating their feasibility and comprehensive impact e.g. on own processes, products and customers' production processes. Figure 1 illustrates the sequential decision making process for RMTI.

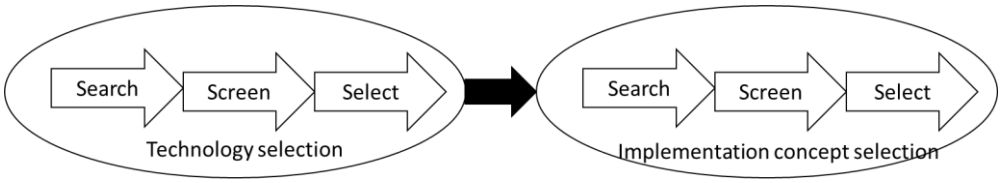


*Figure 1 – Decision making process in case of RMTI ideas*

Overall, RMTI investment proposal evaluation and decision making in the studied projects appears as a logical, team-based process involving the search, screening and selection of the production technology solution. A lot of effort had to be put to the early search and screening, due to the lack of existing ready-made technological solutions. Also the evaluation of the appropriateness of the screened new technology for the purpose of the firm appeared as technically demanding. The selection of the technology and/or the implementation concept was experienced by the interviewees as natural, and it emerged

to decision makers through the screening process quite clearly. In many projects, there was only one viable alternative in the end since others got eliminated during the review, and the final decision making was therefore very straightforward.

*Role of organizational processes versus individuals in the decision making*

All three firms had some processes in place, to support the RMTI decision making. The alignment of investments with the firm's strategic goals was evidently important. Decision making and related evaluations were linked with key customers' needs, product technology roadmaps, and the procedures for investment projects. The organizations had rather rational team-level mechanisms and processes in place, guiding the search and contacting of suppliers, asking for proposals, discussing the proposals in teams, and evaluating them based on explicit criteria.

Despite the rational decision processes, also individual persons had a clear influence on the decisions. Individuals stood out in their contributions particularly during the search for ideas, moving in the right direction, and selecting the right direction among alternatives. Here the persons' depth of technical expertise was valuable. As an interviewee summarized: *"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".* The suitable technology idea sometimes emerged through serendipity, chance events and conversations with the right people or visiting the right firms, and coming across breakthrough ideas and information in other ongoing research. For example, as the interviewee in project B3 summarized how they came across the technology idea: *"In real life there, wasn't any other possibilities to solve. I was lucky to, meet a, partly retired fellow!"*

*Risks and managing them in RMTI decision making*

RMTI involve piloting of a new technology in the production processes of the firm, and in some projects also piloting prototype equipment and unproven technologies. Thus, technological and commercial risks and uncertainties are inherent to RMTI. We analyzed the reasons for firms to accept technical risks in the RMTI projects. Two primary factors guided the firms' risk-tolerance toward non-familiar, non-proven technologies: strategic need or target, and the investment project replacing a bad old technology.

Strategic need refers to a burning need for the new technology. For example in one project, the key customer started such a new product development program that required components with much higher accuracy, and this implied shifting to tolerance levels beyond the capacity of the focal firm's existing processes. Therefore, finding a new technology for the manufacturing process became quite urgent. As the interviewee explained: *"Because this customer is identified as one of our key customers and this was clearly a very very important project for them, we saw this that it is not the right time to calculate that well there are big risks…".* Strategic targets stem from strategic goals and development priorities: the firms had annual plans and three to five-year technology roadmaps to renew existing capabilities, meet product roadmaps, anticipate stringent regulations, and finally, expand markets.

Replacing outdated or inefficient technology and renewing production capability was a necessity for firms when there was already a commercial justification available. Managers in the investment planning team of some of the RMTI projects wanted to maximize the return on investment. Either they saw that the current technology would not be sustainable for a longer time, or it was already outdated, compared to competition or customer needs. By elimination, there is just the radical choice of renewing the technology completely, as an interviewee explained: *"I think the drive was that the other*

*option was just bad.. we have kind of two options here, the bad old one and the risky new one"*. In all projects, the alternatives available were scarce, in terms of how many alternate technologies they knew, and how many alternate suppliers were available. The three firms differed in terms of the business context, and it affected the technology possibilities. The nature of the product and industry segment implied for some projects the unavailability of any mainstream equipment suppliers for their production, and the need to develop and build the equipment needed.

Risks typically present in RMTI proposals at the time of decision making were technical risks due to equipment being a prototype for the equipment supplier firm and pilot trial in exact industrial context of the manufacturing firm. There was also uncertainty about production economics parameters such as speed of production, anticipated volumes, and therefore unit costs, and other product quality parameters. In some projects where RMTI were linked to launching a new product with better specifications, the demand volumes expected in the near future were uncertain, except for demand from key customers.

The measures that gave confidence in taking the above risks included confidence in technology choice, for example interviewee in projct A2 commented "*the test runs that were implemented at the supplier side were rather conclusive…we were quite convinced that yes it makes a very nice edge. So it meets our expectation in that regard (performance on the key parameter for switching to new technology*)". Confidence in the equipment supplier firm's capability and commitment to the needed development work was also an important enabler of accepting the technical risks and uncertainty. The confidence was based on previous successful projects with the supplier, or was based on critical review of the supplier's technical capabilities and strategic interest in this RMTI project. A related aspect was confidence in the plans for implementation. In project A3, a consultant was employed specially for support in the decision on supplier and implementation concept selection: "*we used the services of a former employee who is nowadays a consultant…and he was kind of challenging the suppliers' designs and calculations and expectations and material selections, if for no other reason then at least for the reason of making them make it double sure that they know what they are saying*". In cases where the RMTI project would impact the quality of product, an important confidence generating factor was involvement and positive feedback of key customer(s).

There were also projects where technical failures occurred eventually after the investment decision was made (projects A2, B2), and these were present where firms went ahead only based on their confidence in the supplier firm, and internally were not sure about the implementation plans specific to this project prepared by the supplier. For example, as interviewee in project B2 reflected: *"But now afterwards I have to say that, there was problems in the process because they have not made this kind of project earlier… this valuation and how we are making the decision is very important in these kind of situations that, there is some technological risk and in that case there was the technological risk, but we believe that this equipment supplier it has supplied us many kind of equipment and so on, and they have done then very well. But in this case, there was problems in the project management."*

*Investment justification criteria*

Strategic needs and targets were drivers of initiating the technology search and evaluation processes in most cases. However, these were not sufficient criteria to justify the decision to invest. As the Sr. VP of products involved in project A1 elaborated: "*For in this case we, the strategical drive for the better layer tolerance was clear. It was coming almost by nature from the fact that this was the most important parameter our customers are looking*

*for. That's what we always talk about with the customers, then we need to move forward. So that was clear. By the time we were narrowing down the technologies and it was clear that there's not going to be a cheap solution, a cheap solution which we could just adapt for our all production so that our all production could change from .3 to .2. It might have led to the conclusion that let's not do it…0.1 would be a product which opens up completely new markets and therefore that was for me and for the decision to seek board's approval it was very important that this technology actually enabled the jump all the way to .1*". Thus, higher benefit than merely satisfying the strategic targets with which the technology search was begun, such as new product, new markets, added economic savings were needed to justify the decision to invest. There was often need for additional pressure, triggers for starting the investment pre-engineering phase once the technology had been identified, such as scope for an investment project (need for additional capacity) in a production mill (project B1, A2), or pressure from key customer to start the development (project A1). Satisfying regular investment justification criteria, such as payback period, integration with existing processes, economic unit costs of production, were also calculated, and there was thus thorough consideration of the impact of the investment.

Besides enough reasons to invest in new technology, enough confidence in technology, equipment supplier firm were also important for justifying the investment proposal. The risks were present, but there was good confidence in taking them. This also highlights the characteristic of uncertainty that is present to the end in RMTI investment proposal, to the point of making decision. As Sr. VP of business development involved in project B1 explained, "*when you have made the research and investigations as long as it's possible, then you just have to make the business case and then either choose or not so, we looked at far as you can, and we thought that there is more to gain*."

**Discussion and conclusions**

The present study explored decision making practices in manufacturing firms on RMTI investment proposals. For this purpose, we gathered data on events and activities in the front end of nine RMTI projects from three manufacturing firms. The firms belong to different industries and are of different sizes. In studying three projects per firm we intended to discover if decision making on risky innovative production investments follows typical patterns, for example, in terms of the key enablers for the decision. We further analyzed the nature of decision making process in RMTI, as a type of radical innovation.

The findings reveal that the early phases of technology identification and evaluation were technically demanding, and the final phase of selection of technology was often easier due to lack of many comparable alternatives. This is contrary to the dominant focus in previous studies on the problem of selection from among technology alternatives (e.g. Ordoobadi, 2012; Chan et al., 2006).

Strategic needs and risks were observed to play an important role as motivation and justification for the decision making, thus supporting findings from previous research regarding high relevance of strategic needs in justification of advanced manufacturing technology (e.g. Chan et al., 2006; Iakymenko et al., 2016).

Organizational process for investment projects was utilized in the studied cases, and at times organizational process for new product development projects within product research and development team was also used in the early period. The projects were thus driven by organizational processes and team-based decision making practices were used. However, role of individuals was observed in picking right direction for search for technology solutions. This is in line with observations in previous research focusing on

radical technologies, where individuals impact how radical technologies capture attention in organizations (e.g. Kammerlander and Ganter, 2015).

The topic of decision making on radical process innovation ideas has been less understood in previous research, and the study thus contributes to call for further empirical research in manufacturing firms on processes for developing ideas and concepts for radical process innovations (Kurkkio et al., 2011; Frishammar et al., 2016). This study also expands previous knowledge on the creation of RMTI, from the perspective of manufacturing firms (e.g. Reichstein and Salter, 2006; Keupp and Gassmann, 2013). The findings open up decision making in context of risky innovative production investments and illustrate where RMTI projects are similar to and different from regular investment projects. The results have implications for practice, in terms of providing a framework for supporting management of decision making in these high risk, high benefit investments for manufacturing firms.

Limitations of the research include the small sample of RMTI projects and some topics in decision making research, e.g. political process, are not visible in these projects. Also, the use of decision making systems, e.g. IT based systems, in decision making on RMTI remains a question mark since the projects have not provided any evidence on their use. Further research is encouraged concerning other decisions in the RMTI projects besides the investment decision, including possible cancellations, changes, and reorientations. Also, exploring the prioritization and negotiation processes taking place in firms' management teams concerning RMTI projects could be an interesting avenue for further research. Furthermore, the managers' ways to acquire information and, thereby, reduce the uncertainty in RMTI investments could be studied further.

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