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Design parameters for smart manufacturing innovation processes

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Abstract

Smart manufacturing is considered the corner stone of the next industrial revolution. However, in order to fulfill the requirements of the fourth industrial revolution, radical process innovations are required on manufacturing systems. To achieve this efficiently, the innovation process should be designed properly. This paper, therefore, investigates which parameters in the innovation process design that influence the innovation outcome in the context of smart manufacturing and thus what should be accounted for in the design of innovation processes for smart manufacturing. The research is based on empirical evidence from 18 manufacturing companies and suppliers of manufacturing technology.

Keywords: Innovation process design; innovation; smart manufacturing; industry 4.0; process innovation; manufacturing process innovation; innovation process; design parameter.

1. Introduction

The current technological development is providing promising opportunities for manufacturing process innovation leading the manufacturing industry through a paradigm shift, which is now counting the fourth industrial revolution. The fourth industrial revolution has also been denominated Industry 4.0.[1, 2] The overall aim of Industry 4.0 is to realize a manufacturing batch size of one at the cost of mass production, thus enabling production of individualized products at a reasonable cost by the use of smart manufacturing systems [3]. Achieving this will strengthen the competitiveness of manufacturers located in high-wage countries such Denmark and Germany [4, 5]. However, smart manufacturing puts forth new requirements to the manufacturing system such as increasing manufacturing flexibility [6]. Industry 4.0 strives to accommodate these new requirements by introducing smart manufacturing systems made of intelligent end-to-end processes throughout the supply chain. This made possible by the use of technological solutions such as intelligent decision-making and cyber-physical systems.[5, 6]

In order for manufacturing companies to utilize these smart manufacturing technologies on their own manufacturing systems, manufacturing process innovations must take place locally in individual manufacturing companies [6]. A manufacturing process innovation is the result of an innovation process. To achieve results efficiently, the innovation process needs a proper design. However, research studying the design of innovation processes for manufacturing process innovation is scarce, and almost not existing in the context of smart manufacturing. Consequently, to support manufacturing process innovation in the context of smart manufacturing, more research is needed in this area.

In order to efficiently manage manufacturing process innovation processes in industry, a deeper understanding of which design parameters should be present in the design of the innovation process is needed. By identifying these parameters and accounting for them in the innovation process design, the innovation performance can be improved, which is desirable in industry.[7, 8] Despite its relevance to industry, research on manufacturing process innovation is scarce [3, 9-11]. Existing research is among other things focusing on studying the effects

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of one or a few parameters to a company's innovation performance. Hall et al. [12] for instance studied the relation between firm size, R&D intensity and investment in equipment, and the likelihood of product and process innovation, Zeng et al. [13] studied the relation between cooperation between firms, cooperation with intermediary institutions, and cooperation with research organizations, and its effect on SMEs' innovation performance, and Lassen and Laugen [14] studied the effect of internal/external collaboration on the degree of innovation. As mentioned such findings only focus on a few parameters which may affect the innovation outcome. Therefore, in order to ensure a measurement system covering the full innovation process additional parameters must be included. Previous research which has applied a systems perspective to this are e.g. Beroggi and Cardinet [8] who designed a generic model for innovation indicators throughout the innovation process, and Dziallas and Blind [7] who studied innovation indicators throughout the innovation process for product innovation based on an extensive literature review. However, we argue that the underlying circumstances of manufacturing process innovation in the context of smart manufacturing are different from those of product innovation which implies that innovation processes for smart manufacturing need to be designed for this purpose. Consequently, research in this field is needed. In this paper we therefore aim to define parameters in the innovation process which have a positive influence on the innovation outcome in the context of smart manufacturing by posing the research question: *Which parameters in the innovation process design positively affect the innovation outcome in the context of smart manufacturing?*

The paper is organized as follows: In section 2, the applied research methodology is presented, section 3 presents the findings which are discussed and concluded in section 4.

2. Research methodology

Despite that research in smart manufacturing is growing, research in innovation processes for smart manufacturing is nascent and a research approach suitable for research in an immature knowledge field is therefore needed. Case study and action research are examples of research approaches suitable for this purpose. As opposed to case study research, action research allows the researcher to actively participate in the (innovation) process which is highly valuable when studying a nascent research field where both academia and industry are unexperienced. Consequently, by allowing interaction between researchers and participants from industry during the research process, both parties can continuously contribute to designing the process.[15] Therefore, action research was chosen as research approach for this research. In action research, data resolves as a result of interventions and it is not possible to control the outcome as this depends on the participants' reaction to the intervention. This means that action research leads to results not only explaining a phenomenon as it appears in steady state but also a deeper understanding of how the phenomenon reacts to changes.[15]

This research has taken place in the research programme "Innovation Factory North". The companies participating in the programme are part of an open innovation formation consisting of a combination of manufacturers, manufacturing technology suppliers, and nine researchers from Aalborg University. The overall purpose is to collaborate on developing smart manufacturing innovations and by doing so utilizing knowledge and experience from the other participating companies and the university. The research programme follows the three phases of an innovation process: Ideation, development and implementation. In each phase, the companies have conducted and participated in a number of activities which have provided the data for our research. The activities in each of the phases are presented in Figure 1.

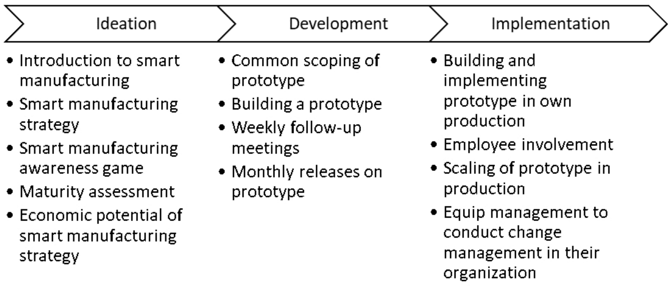

Figure 1: Activities in the research programme

The selection criteria for the companies participating in this research are: 1) Companies of different sizes and from different industries should be represented to allow for broader generalization of the results, 2) The companies must participate actively in the research programme and thus the innovation process, 3) All in all, all stages of an innovation process must be represented; from ideation to implementation.

In total, data from 14 manufacturing companies and four suppliers of manufacturing technologies contributed to this research. Table 1 shows an overview of the companies, their size and their representatives in the programme. As the table shows, the companies are a mix of small, medium and large enterprises coming from different industries, and are thus subject to different challenges in their internal operations. Moreover, the companies contributing to this research were at different stages of the innovation process at the time of data collection. No companies had completed the implementation phase which means that it has not been possible to measure the results of this phase. Therefore, only findings related to the actions which have occurred at the point of data collection in the implementation phase are presented.

The data set consists of a mix of semi-structured interviews, video recordings, statements and observations from meetings held in connection with the research programme. The participants from the companies are e.g. managing directors, technology managers, production managers, production developers, technical engineers, sales directors, and project managers. Additionally, a lab engineer who has a central role in supporting the companies in the development stage of the research programme was interviewed. All material was transcribed and analyzed in the NVivo software using the Gioia methodology. The Gioia methodology is a systematic approach designed to bring scholarly rigor to qualitative, inductive research by demonstrating evidence of findings and conclusions. The methodology uses a systematic presentation

Table 1. Overview of companies and participants

Company	Company size	Company participants
Supplier 1	Small	CTO
Supplier 2	Small	CEO, Consultant
Supplier 3	Small	CEO, Machine learning engineer
Supplier 4	Small	CEO
Manufacturer 1	Medium	CTO
Manufacturer 2	Small	CEO, CFO, Production manager, Master student
Manufacturer 3	Small	COO, Production developer
Manufacturer 4	Large	Project manager, Technical project manager, Technology contributor, Industrial PhD fellow
Manufacturer 5	Large	Head of product and process documentation, Head of performance management, Production specialist, Production engineer
Manufacturer 6	Medium	CTO, Sales director
Manufacturer 7	Small	CEO, Technical engineer
Manufacturer 8	Small	Specialist, Order processor
Manufacturer 9	Small	CEO, Production manager
Manufacturer 10	Large	CTO, Section manager, Business digitalization project manager
Manufacturer 11	Medium	Production planner, Project manager, Vice president of supply chain and manufacturing
Manufacturer 12	Small	CTO, Production manager
Manufacturer 13	Small	CEO, Business development manager
Manufacturer 14	Medium	CEO, CTO

of a “first-order” and “second-order” analysis. In the “first-order” analysis informant-centric terms and codes are analyzed which afterwards are translated into researcher-centric concepts and themes, and finally combined into aggregated dimensions in the “second-order” analysis.[16]

3. Findings

In this section, the results of the data analysis are presented. The findings are organized according to design parameters of the innovation process which influence the innovation outcome. Table 2 shows an extract of the data analysis.

3.1. Smart manufacturing strategy

Smart manufacturing innovation requires a clear smart manufacturing strategy. The strategy should be used as a guiding principle for making decisions for new innovation projects in order to ensure that all new projects contribute to fulfill the overall strategy. As one interviewee puts it: “*[The manufacturing strategy should] create a common understanding in regard to what actions will move us in the right direction*”. This is consistent with the findings of Biegler et al. [17], and Chen and Zhou [18], who identified setting a strategy as a critical success factor for smart manufacturing innovation.

Furthermore, taking decisions based on an overall strategy at the same time supports the manufacturers to move the focus of manufacturing system innovation away from being technology driven and instead focus on projects which have the potential to optimize the whole manufacturing system rather than parts of it.

One of the companies explains that setting up a strategy also supports the anchoring of the innovation, as this can be a way of reducing the shop-floor workers’ resistance to change, provided that the management is able to communicate the effect it will have on the shop-floor if the strategy is pursued.

Consequently, it is concluded that setting up a smart manufacturing strategy is important in order to efficiently control that the initiated smart manufacturing innovation projects support the fulfillment of the strategy. In addition to this the findings also show, that laying down a smart manufacturing strategy affects the shop-floor support of the innovations.

3.2. New designs of innovation processes for smart manufacturing

The results, furthermore, indicate that different aspects of the design of the innovation process itself impacts the innovation outcome. In total, three aspects were identified: Shorter development times, agility, and consideration of horizontal and vertical integration to the manufacturing system.

3.2.1. Shorter development times

The results show that it is beneficial if innovation processes for smart manufacturing have short development times as this may provide faster results. According to one of the participating companies an explanation for this is that when development times are short, the employees of the individual organizations stay motivated in the project which supports its progress. Theory often states that there is a need for shorter development times from a market perspective, namely in order to reduce time to market (see e.g. [3, 6]). However, as these results indicate withholding the motivation within organizations may also be a vital factor for keeping development times short. The motivation itself may also boost the project progress and may thus also support the achievement of results in the project. The way the project is organized might also support the progress of the projects. The reason for this is that the project has monthly milestones, which all participants must meet before the project can continue. Thus, if a company is delayed, this will delay the project for all other companies in the project as well. Being held up on providing results on the project from an external partner may also have put additional pressure on the companies which may have had impact on the results. Furthermore, since the project is an open innovation collaboration, it also requires a team effort from all participating companies in meeting milestones to avoid delaying the project for the other participating companies. The open innovation collaboration may, therefore, also be a way of achieving shorter development times.

Table 2. Extract of data analysis of first- and second-order based on quotes.

Quote	First-order	Second-order
"setting a goal for innovation and digitalization"	There should be an overall goal for digitalization and innovation initiatives.	Smart manufacturing strategy
"what digital processes can we use to support achieving the goal and in that way do it in the right order"	Digitalization initiatives should aim at achieving an overall goal.	Smart manufacturing strategy
"create a common understanding about what can actually advance us I think that is important"	There should be an overall goal which known throughout the company so that initiatives are aligned and aim to fulfill the overall goal.	Smart manufacturing strategy
"[it is] very important that the stages of the innovation process are densely packed. There should always be a push to fulfill the upcoming goal"	Short development times create a push to achieve goals.	Short development times
"it takes time, but it cannot take too long. Because then you risk that those 30% who were originally enthusiastic about the project they begin to doubt whether the project will ever finish"	Short development times are needed to keep employees motivated in the project.	Short development times
"We have gotten further [with the prototype] in four months compared to other, similar projects which we have been part of, and they have sometimes even lasted for a longer time period as well."	Even though development times are short, the progress within the time frame is greater in comparison to projects with a longer time frame.	Short development times
"What journey are we on and where should we start? To be sure that we do not make short-term decisions which might have long-term consequences"	They do not know where they are going, so they need an innovation process which can account for these uncertainties.	Agile innovation process
"This is not a project it is a progressive journey starting from where you are in terms of technology right now to a place we do not know where is right now but which is valuable to the respective production facility."	The end-goal is unknown, which requires a process that can evolve as the project progresses.	Agile innovation process
"If we have a "guiding star" how do we then navigate from the new knowledge we continuously obtain"	The innovation process is a learning process. The participants learn throughout the process and the innovation process therefore needs to be able to absorb this new knowledge.	Agile innovation process
"You cannot just invest in new technologies. You have to invest in systems which the new technologies are going to be part of".	Technologies must be integrated into a system to create value.	Vertical and horizontal integration
"You have remarkable investments in existing production equipment, which should be kept, however you can invest in new technologies which can be integrated with the existing equipment"	Existing production equipment can be improved by integrating new technology.	Vertical and horizontal integration
"Everyone brings in something different and has different agendas"	The participants bring in different viewpoints to the discussions.	Open innovation
"I don't think they would have gotten as far in the same time"	Open innovation collaboration contributes with knowledge which can reduce the resources spent.	Open innovation
"Exchange of challenges and experiences with other companies has benefitted. It has provided the opportunity for the participating companies to take example from companies who have been or are in similar situations."	Learn from the other companies.	Open innovation
"It is necessary to build a physical demonstrator in our own production facilities [...] it creates transparency to be open about what we are doing"	A prototype (demonstrator) signals transparency in the organization about the project.	Prototype
"We shouldn't try to take the easy way out. We have to take the long, profound way. Then I definitely believe that there is a greater chance that we reach our goal since we have built up all the experience that we need along the way."	Building a prototype lets the company learn about building the solutions and which pitfalls they should be aware of. This gives the experience to build the final solution afterwards.	Prototype
"Production automation and implementing a robot in the production is tangible solutions but data automation is one step further. How do we proceed with these kinds of solutions?"	Prototypes are needed to make solutions tangible.	Prototype
"We cannot do this if we do not have the whole company onboard"	Employee involvement is necessary to reach the goal.	Employee involvement
"I don't think you should be scared of the employees feeling threatened if you just involve them"	Employee involvement is necessary to avoid resistance.	Employee involvement
But in a company like ours you don't just talk to the people in the production about [the new sensor solution]. You also need to talk to the people in the administration about what this is."	Employees need to be involved in digitalization projects such as installing sensors.	Employee involvement

3.2.2. Agile innovation process

The smart manufacturing strategy comprises the overall goal, which should be achieved through several smaller efforts. Both researchers and companies refer to this as a journey. On this journey the companies absorb new knowledge and navigate through the process based on this in order to achieve the final destination; the smart manufacturing strategy. Being able to do so requires an agile innovation process. Introducing agility to the innovation process for smart manufacturing has already been suggested in literature (see e.g. [6]) as a way to follow the rapid technological development. However, the findings of this research have identified several other causes to use agile innovation processes in the context of smart manufacturing.

In this project, small iterations have been used to achieve agility. To give an example, one manufacturer wanted to build a prototype on a machine in their production which would count the number of scrapped products from the machine output. However, building such a solution was not straight forward and required experimenting with different setups before attaining an operable solution. The learnings from each successful and unsuccessful step in the experiments were used to support the direction of the subsequent experiment.

Many smart manufacturing solutions for industry do not exist as ready to implement solutions, but the technology which it may build on is available and from that a solution can be constructed which fits the needs of the individual company. This forces manufacturing companies to either take on the responsibility of managing the construction of smart manufacturing solutions or buy this service from an external provider.

As mentioned, the research programme has among others used iterations to achieve agility. The time of an iteration in the project is approximately one month, which is not much time for building a prototype from scratch. This means that the progress from one iteration to the next is small. However, the results have shown that by using short iterations everyone irrespective of prior experience with the technology can keep up. This indicates that using an agile approach supports the innovation outcome as it supports the companies in successfully progressing with the prototype development independent of prior experience with the technology.

3.2.3. Vertical and horizontal integration to the manufacturing system

The findings furthermore indicate, that smart manufacturing innovation processes should account for the vertical and horizontal integration in the manufacturing system. The integration to the manufacturing system is one of the overarching elements of smart manufacturing [19].

In the beginning of the development phase on a project focusing on capturing data by the use of sensors in the production, actors from the participating manufacturing companies were highly focused on a specific application of the captured data in their communication. The applications were narrow applications such as registering whether a machine is running or not. When encouraging the companies to propose conceptual applications of the same data but with a broader scope which would embrace vertical or horizontal integration the companies were lacking ideas. The narrow scope restricted the discussions in the project and implied that the potential of the prototype was highly limited. From this it was clear, that if smart manufacturing innovation processes should take vertical and horizontal integration into account, tools were needed to support this way of thinking. Consequently, to support the companies to allow for vertical and/or horizontal integration it was decided to ask the companies to make user stories and through these explain the use of the prototype and thereby its value. Composing user stories were a success. Following, the discussions held a broader and sometimes also more conceptual perspective which increased the usefulness of the prototype.

3.3. Open innovation collaborations

The participants have different agenda: Suppliers of manufacturing technology are interested in developing products corresponding to the needs of manufacturers, manufacturers are interested in different types of application corresponding to their needs, and researchers are interested in new aspects of their research fields. Qua these differences the mix of participants in the open innovation collaborations bring in different aspects and topics to the discussions. This has proven to be highly valuable to the participating companies, and has among others brought inspiration for new product innovations for suppliers of manufacturing technology and inspiration for new application opportunities of smart manufacturing for manufacturers. Additionally, among manufacturers, the open innovation collaboration has also been used for exchange of experience, and thus assists the companies in improving the innovation process internally. The innovation outcomes of the open innovation collaborations have been identified in both the ideation and the development phases. These findings indicate that open innovation collaborations positively impact the innovation outcome. However, it is still to be determined how to combine companies in open innovation collaboration in order for all companies to get the most from the collaboration. The preliminary results of the projects in the research programme indicate that more than two manufacturing companies are needed in the collaboration in order to fully utilize the potential of open innovation collaborations, but at the same time, a collaboration between eight companies is too big.

3.4. Building a prototype

The results indicate that building a prototype in the development phase has a positive impact on the innovation outcome for several reasons. The prototype provides hands-on experience in the companies about how to build smart manufacturing solutions and which challenges that may occur. It is important that the complexity in the solution is built up one step at a time, as one of the manufacturing companies states:

"*We shouldn't try to take the easy way out. We have to take the long, profound way. Then I definitely believe that there is a greater chance that we reach our goal since we have built up all the experience that we need along the way*."

Furthermore, the prototype is important for eventually implementing the solution in the production as it requires ownership from the company and employee involvement. It also creates transparency towards the other employees who are not actively participating in the project and it shows openness.

Lastly, since smart manufacturing relies on processes which are integrated through data exchange, many smart manufacturing solutions are intangible which comprises a mental barrier in companies.

3.5. Employee involvement

To succeed with the implementation of the innovation, employees in manufacturing companies should eventually be involved. This not only concern shop-floor workers but also administrative employees and the joint consultative committee. As previously described, the prototype can be a great way of introducing the employees to the project. However, to avoid a decrease in enthusiasm during the project, employees should not be involved too early. Consequently, a simple prototype should be in place before involving employees.

4. Discussion and conclusions

This research aimed to answer the research question: *Which parameters in the innovation process design positively affect the innovation outcome in the context of smart manufacturing?*

To answer the research question, a structured data analysis was conducted based on data from 18 manufacturers and suppliers of manufacturing technology. The purpose of the data analysis was to explore which parameters have a positive impact on the innovation outcome in the innovation process design. Unlike related research, this paper provides an extensive overview of which parameters affect the innovation outcome throughout the whole innovation process from ideation to implementation. This contributes to a better holistic understanding of what may have a positive impact on the innovation outcome. From the parameters presented in section 3, seven design parameters for smart manufacturing innovation processes have been extracted. One parameter has been defined for each of the three phases. Additionally, four parameters have been identified which should be present in all three phases of the innovation process. This is summarized in Figure 2.

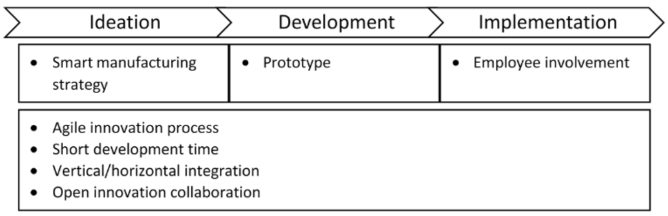

Figure 2: Design parameters for smart manufacturing innovation processes

A shortcoming of this research is that it has not been possible to measure the innovation outcome of the implementation phase for which reason future research should include data on this part of the innovation process as well.

Furthermore, as the research is based on qualitative data it has not been possible to determine whether any of the parameters are correlated. Thus, future research could study this by using quantitative data.

Several of the identified parameters support findings in existing research on innovation process design. However, some parameters stand out. This is for instance the impact of building a prototype, and using open innovation collaborations. Therefore, how to design innovation processes which utilize the potential of these is of particular relevance to explore further in future research.

The findings of this study also reveal that tools and methods supporting activities in the innovation process which have a positive impact on the innovation outcome are lacking. Consequently, future research should study tools and methods which can support manufacturing companies in conducting activities with a positive impact on the innovation outcome.

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