Triple Helix Collaborative Innovation and Value Co-creation in an Industry 4.0 Context

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Abstract: Digitalization and Industry 4.0 promote a fundamental technological disruption that requires industry, research and government institutions to revisit their roles within the innovation ecosystems. Actors in this environment need to understand value co-creation during interaction and collaboration. The purpose of this study is to investigate the triple helix collaborative capabilities in an Industry 4.0 ecosystem context. The case under study is a Finnish national publicly funded research project involving five global manufacturers, three research institutions, and several small- and medium-size enterprises (SMEs). The results demonstrate that practices related to adaptivity, experience sharing, SME co-innovation and scale up can enable the ecosystem to be managed in a dynamic way. Yet, this type of operation requires the adoption of the ecosystem approach with mutual trust, intensive collaboration and the identification of common aims among the project participants. The presented co-innovation model can be used to design innovation ecosystem projects in the future.

Keywords: *Collaboration; capabilities; Industry 4.0; innovation ecosystem; triple helix; value co-creation*

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1 Introduction

Industry 4.0 is represented by a policy-driven innovation discourse in manufacturing industries that involves the institutionalization of innovations systems from the triple helix perspective, i.e. businesses, academia and government (Pfeiffer, 2017; Reischauer, 2018). Based on documented evidence in research (Fatorachian and Kazemi, 2018), governmental reforms (Mexican Ministry of Economy, 2016) and practical reports (Kagermann et al., 2013), it is believed that the adoption of Industry 4.0 will provide an extensive body of benefits. A key claim with regard to technological dynamism and industrial advancements is that Industry 4.0 necessitates manufacturing and service-based industries to change and innovate their work and management structures (Krishnamoorthy and Damle, 2017; Li, 2018; Reischauer, 2018; Schwab, 2016; Sung, 2018). These changes will create a new competitive environment which requires new business models (Weking et al., 2019), improved processes, strategies and competencies (Camarinha-Matos et al., 2009). These organizational transformations shape the industries in a systemic way and empower people with new capabilities at an individual level, thus creating shared value (Kim, 2017).

The ongoing disruptions of Industry 4.0 in terms of emerging technologies and innovations are a call to rethink for companies, universities and government institutions that form the triple helix. They must shift their focus from linear innovation models of only internal knowledge and value creation, which limits sustainable operations and performance of businesses, to a systemic, innovation-based ecosystem that promotes network collaboration to understand individual and aligned value creation and value systems (Weber, 2011; Sun et al, 2018; Rong et al, 2015; Camarinha-Matos et al., 2017). This requires the triple helix actors of the innovation ecosystem to explore and evaluate the utilities and risks associated with the emerging technologies (Kim, 2017). It is well established that triple helix research mostly explores the context of developed countries (Yoon and Park, 2017), which have well-known innovation systems, well-developed institutes and enterprises, top-ranking universities and robust R&D centres (Kafouros et al., 2015**)**. Research has also shown that there are fundamental differences in the development and applicability of the triple helix model, as it faces varied institutional barriers, such as rigidity and fragmentation (Van Geenhuizen, 2016), in diversified national contexts (Yoon, 2005). To overcome such barriers, close collaboration between universities and firms through experimentations with active experience sharing could be the first step to create a seedbed for triple helix development that results in the growth of the knowledge economy (Van Geenhuizen, 2016). Moreover, in line with technological advancements and industrial evolution, good practices in innovation systems development need to be analysed and refined (Ranga and Etzkowitz, 2013). Within these systems, a concurrent understanding of the involved organizations and their patterns of collaborations that lead to effective manufacturing systems is crucial (Camarinha-Matos et al., 2009; 2013) and requires further attention as an important research problem (Camarinha-Matos et al., 2017). To address this research problem, the present study empirically analyses the triple helix collaboration as a boundary-spanning activity which includes all the processes required to achieve value co-creation and innovation, by connecting the actors, developing trust and commitment, and sharing ideas and experiences (de Moor et al., 2010) in a unique innovation ecosystem project. Collaborations taking place in an Industry 4.0 environment become more complex when it involves distinct set of players and their complex interactions. This signifies the ecosystem perspective for this study as it focuses on the co-creation of value through collaborative networks (Rusell and Smorodinskaya, 2018). Based on the synthesis of our findings and existing research, this article aims to illustrate the crucial factors that affect the success of triple helix collaboration in an Industry 4.0 environment. This aim is supported by the following research questions.

- What type of triple helix collaboration is required for value co-creation in Industry 4.0 innovation ecosystems?
- What are the enabling factors and how can they be utilised to implement Industry 4.0 triple helix collaboration in practice?

The rest of this paper is structured in five sections. In Section 2, the concepts of triple helix innovation ecosystems, collaborations and the respective capabilities leading to value co-creation in the Industry 4.0 context are characterized based on the literature. This is followed by the research methodology and materials, which are presented in Section 3, as well as a brief introduction of the case explored. Section 4 describes the key results of the case study. Section 5 contains a discussion of the results, including an illustration of the enabling factors required in practice for Industry 4.0-based triple helix collaborative innovation. The paper closes with section 6, which contains a brief conclusion of the paper and future research paths.

2. Literature Review

2.1 Innovation ecosystems and value co-creation

The ecosystem concept has become popular in industrial discourse, academic literature and innovation policy debates (e.g. Benitez et al., 2020; Majava et al., 2020; Rinkinen and Harmaakorpi, 2019). The aim of the ecosystem viewpoint is to develop ‘*both the network-based organizational design and the collaborative organizational culture of the emerging innovation-led economies*’. [Smorodinskaya et al. (2017), p. 5252]. Here, we distinguish between different types of ecosystems: *business ecosystems* can be viewed as value networks that cross regional and national boundaries, whereas *knowledge ecosystems* and *innovation ecosystems*, typically, are centred spatially around universities and public research organizations (Clarysse et al., 2014). In terms of focus, business ecosystems concentrate on value creation and knowledge ecosystems concentrate on the generation of new knowledge and technology, whereas innovation ecosystems integrate both the knowledge and business ecosystems.

In a technologically disruptive setting, innovation can be nurtured through collaboration in an ecosystem environment developed for value co-creation (Smorodinskaya et al., 2017). Innovation ecosystems can be seen as multi-layered systems combining the multilateral connections of heterogenous partners aiming to innovate for productivity and value (Visscher et al., 2021). These innovation ecosystems can be defined as ‘collaborative arrangements through which firms combine their individual offerings into a coherent, customer-facing solution’ (Adner, 2006) or ‘dynamic collaborative networks of people and organizations formed around projects with an innovation objective’ (Smorodinskaya et al., 2017). The features that discern innovation ecosystems from other regional innovation-centric concepts include a greater appreciation for connections among actors, the vital role of information and communication technology (ICT), open innovation and the importance of market forces as opposed to government push (Oh et al., 2016).

The evolution of innovation ecosystems can be divided into different lifecycle stages (Benitez et al., 2020). In the *birth phase* of innovation ecosystems, actors can be assigned any of four roles (Dedehayir et al., 2016): leadership roles, direct value-creation roles, value-creation support roles and entrepreneurial-ecosystem roles. The role of research institutions is vital during the birth phase, and in this phase, actors can shift roles and assume multiple roles simultaneously (Dedehayir et al., 2016). Besides research institutions, large companies should have a bigger role in supporting innovative start-ups and the development of regional ecosystem (Clarysse et al., 2014). Additionally, public procurement should also be considered as a possible stimulus for the creation of new ecosystems (Clarysse et al., 2014). Finally, the factors that affect the successful implementation of innovation ecosystems include continuous investments in infrastructure, systematic risk evaluation, assignment of clear roles and openness to chaos and failure (Durst and Poutanen, 2013).

Modern economics literature implies that the process of co-creation relies on knowledge and collaborations in environments that enable joint information sharing (Goermar et al., 2021). It enables collaboration between different actors, allowing them to co-create new values and goods that contribute to innovations, and thus, lead to the development of an innovation-led economy (Smorodinskaya et al., 2017; Hyrkäs et al., 2020). Value co-creation is considered as a business strategy that focuses on an active relationship between producers and consumers where consumers can act as workers and design articulators of the organization. It can be defined as an active, creative and social process that is based on collaboration between producers and users (Roser et al., 2009). Value co-creation targets the interaction mechanisms for collaboration, knowledge creation, sharing and transfer (MacGregor and Carleton, 2012).

2.2 Industry 4.0 and the triple helix innovation ecosystem

Adoption of digital technologies has tremendously increased during the last two decades. These technological developments are expected to result in a long-term economic uprise in terms of reshaping economic and social life (Ayres, 1990; Korotayev et al., 2011). Further, digitalization has assumed a paramount role in shaping the contemporary manufacturing industry (Reischauer, 2018) and is the basis of Industry 4.0, which is considered as a new industrial revolution (Schwab, 2016). The technological disruptions have challenged research institutions to move towards experimentation, learning by doing and design thinking, which involves inter-disciplinary communication (Brown and Katz, 2009; Kim, 2017) and requires knowledge as an imperative for Industry 4.0 technologies (Lepore et al., 2021). Likewise, SMEs, which typically have limited resources, need to collaborate with other private organizations and triple helix actors to increase their access to a wider expert pool and financial volume for new business opportunities (Camarinha-Matos et al., 2009). Furthermore, the changing nature of technological developments associated with Industry 4.0 calls for triple helix actors to seek governance structures that are suitable for seizing these opportunities and co-creating value through collaboration (Kim, 2017).

Reischauer (2018) argues that Industry 4.0 represents a comprehensive movement that enables policy-driven collaborative innovation through discourse, and its underlying aim is the development innovation ecosystems and sustainable growth. Industry 4.0 becomes, in this context, a platform where the actors co-evolve, enhancing each other’s performance, while assuming relative autonomy in the innovation space (Etzkowitz and Zhou, 2018). Approaching Industry 4.0 from a triple helix viewpoint allows the actors to adapt it according to their own interests, while simultaneously ensuring mutual benefits from the collaboration (Reischauer, 2018). This view is supported by Clarysse et al., (2014), who state that innovation policies should focus more on an ecosystem approach instead of bilateral connections between organizations. According to the triple helix approach, academia becomes an enabler of entrepreneurship, thus promoting firm formation, while the industry assumes a vital role in advancing research and providing high-level training. Further, the responsibility of the government is expanded to include regulation of the whole innovation process (Etzkowitz and Klofsten, 2005).

While the impact of Industry 4.0 on large enterprises has gained much attention, the effect on SMEs has been somewhat overlooked, even though this effect and the contribution of SMEs to value creation is crucial (Müller et al., 2018). Kagermann et al., (2013) provide a dyadic view: some SMEs act as consumers, and some act as suppliers of Industry 4.0 services. Müller et al., (2018) provide another dyadic classification of SMEs as externally and internally motivated SMEs: the former group actively engages in collaboration with new companies and academia, while the latter group is unaware of the potential of such partnerships and, thus, less prone to cooperate. Additionally, SMEs are gauged as being reluctant to embark on digital transformation (Buonanno, 2005; Müller et al., 2018).

2.3 Collaboration and collaborative capability within an innovation ecosystem

Collaboration is defined as a joint plan consisting of different entities which share information, resources and responsibilities to create shared value and achieve a common goal. In the process of collaboration, the entities forming the group can engage with one another through mutual trust, positive competition, commitment, shared risks and rewards, problem solving and overall enhancement of collaborative capabilities (Blomqvist and Levy, 2006; Camarinha-Matos et al., 2017; Brown et al., 2021). Collaborations and commitment play a key role in building collaborative capabilities which are considered as paramount to collaborative innovation (Kumar et al., 2021), as they can manage, shape and develop relationships between partners at the individual, group, departmental and organizational levels (Blomqvist and Levy, 2006).

Collaboration capability can be defined as an ‘actor’s capability to build and manage network relationships based on mutual trust, communication and commitment’ (Blomqvist and Levy, 2006). Trust is a multi-faceted phenomenon (Blomqvist, 2002) which potentially describes actors’ behaviours and their relationships and predicts the risk of their future collaborations (Seppänen et al., 2004). Commitment is measured in terms of solid actions and investments in the relationship (Cullen et al., 2000; Nummela, 2003). The third major component of collaborative relationships is communication. Collaborative communication is a major measure of partners’ collaborative intentions (Mohr et al., 1996; 1999). It accelerates collaborative processes by creating a smooth and supportive working environment which facilitates collaboration for the joint outcome (Morgan and Hunt, 1994). In case a company lacks capabilities for commercialization of innovations, it can gain access to these resources through collaboration (Stojčić, 2021).

Recent studies have found that digital integration in the context of Industry 4.0 benefits the whole value chain (Liao et al., 2017) and enhances decision-making processes (Frand et al., 2019b), systematic learning capabilities and collaboration at all levels (Tortorella, 2020). Therefore, it is significant to consider collaborative capabilities in an Industry 4.0 context, as it entails a transformational capacity to continuously redefine itself with new technological advancements (Garud and Nayar, 1994; Tyler, 2008) that eventually lead to joint innovative solutions.

2.4. Synthesis of the literature review on Industry 4.0 triple helix collaboration in the innovation ecosystem

Figure 1 presents the synthesis of the literature review findings. As discussed earlier, business ecosystems cross regional and national boundaries, whereas knowledge or innovation networks are, typically, centred spatially around universities and research organizations (Clarysse et al., 2014). More specifically, business ecosystems create and deliver products and services to customers, knowledge ecosystems focus on creating new knowledge and technology, and innovation ecosystems integrate the knowledge and business ecosystems. Industry 4.0 transformation involves several disruptions for technologies, operations and business models in the manufacturing industry (Camarinha-Matos et al., 2017), and these disruptions impact the ways in which value co-creation takes place. Effective utilization of knowledge ecosystems for knowledge creation, sharing and transfer are considered vital to address and benefit from Industry 4.0-related disruptions. However, new value co-creation models cannot be created without productive collaboration between different actors participating in the value creation (MacGregor and Carleton, 2012; Smorodinskaya et al., 2017). This collaboration, in turn, emphasizes the importance of collaborative capabilities, i.e. trust, communication and commitment (Blomqvist and Levy, 2006). These three enablers are pertinent with regard to adopting a triple helix approach for industry innovation in the innovation ecosystem. The key triple helix actors in the Industry 4.0 context include manufacturing companies and SMEs, universities and research institutes, and a government that provides funding and guidance for innovation activities. A key element in the triple helix model is boundary spanning (Champenois and Etzkowitz, 2018), according to which the actors take on new roles.

< Insert Figure 1 here >

In fact, boundary spanning can be considered as a catalyst for new technological, process and business model innovations which can accelerate the digital transformation of the industry. These impacts extend beyond local innovation ecosystems, as they also affect global business ecosystems in the manufacturing industry. The transformation has a domino effect, because the accelerated digitalization and changes in business ecosystems cause new disruptions.

3. Research methodology and case description

3.1 Research design

The study uses a qualitative case-study analysis approach (Yin, 2009) that is based on secondary data sources such as project plans, presentations, final reports and a survey. The empirical data include observations and notes made in project meetings, sprint reviews and factory visits by the authors. To further evaluate the success of collaboration, a self-administered questionnaire was distributed among the project participants during 08-10/2019. All the survey items were extracted from the existing literature and were developed to fit the Industry 4.0 context. The survey questions were designed based on an actor-dependency model (Yu and Mylopoulos, 1993), in order to understand the dependencies, problems and benefits from the perspective of the project participants. This model was selected as the basis for designing the survey questions, because it is based on a network-based collaborative environment comprising of organizational actors linked through different type of dependencies. The survey based on the model was designed and modified with the help of two experienced authors and researchers from a national research organization who were working in the field. Further, to ensure that the survey questions were clear and objective, it was pilot tested on the managers of parent companies. Based on their feedback and recommendations, the survey was further modified. Finally, the questionnaire was e-mailed to participants of the Reboot IoT Factory project. All the responses were scored on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

3.2 Data collection and analysis

An e-mail survey was sent to all the participants of Reboot after the project authorities granted their permission. The initial sample consisted of 116 participants from the participating research, factory and SME organizations. The survey included an introductory text which explained that the participants' responses would be kept confidential and asked them to provide their informed consent. It also guaranteed that the results would be shared with the participants if they made a request for the same. The participants were sent two reminder emails within a month, which was the period for which the survey was open. We received 33 useable responses, which made the response rate 28%. Most of the respondents (49%) were from the research partners, and 33% and 18% were factory and SME respondents respectively. In addition to the survey data, we analysed project documentation, project plans, presentations, reports, as well as observations and notes made in project meetings, sprint reviews and factory visits. The data analysis was based on qualitative content analysis (Krippendorff, 2018; Schreier, 2012) to benefit from a structured approach and make the data more systematic and flexible (Schreier, 2012). During the analysis, first the coding frame was established based on the broad description and interpretations made. The core categories were identified and labelled as 'first-order concepts', such as innovation ecosystems and knowledge ecosystems. Then, the sub-categories were extracted and defined, which linked the broader concepts as 'second-order themes' such as triple helix boundary spanning. Finally, 'aggregate dimensions' were found by connecting second-order themes and first-order concepts, such as experience sharing.

3.3 Case study of triple helix co-innovation

The setting examined in this paper is the Reboot IoT Factory project (Reboot IoT Factory 2020), a national innovation project that aims to speed up the digital transformation of the manufacturing industry in Finland. While Finland possesses a high level of expertise in ICT and Internet of Things (IoT), a key challenge has been the rapid integration of this expertise into manufacturing environments to enable fast industry transformation and global competitive advantage. The project approached triple helix innovation in a non-traditional manner, which along with the timeliness of digitalization and Industry 4.0, make it an interesting research case.

Our study focuses on the project's first phase, which took place between June 2018 and

October 2019. Phase I was funded by a national funding body (Business Finland), and the project consortium initially consisted of five global manufacturing companies (ABB, GE Healthcare, Kongsberg Maritime, Nokia and Ponsse) and three research institutions (VTT Research Institute of Finland, University of Oulu and Åbo Akademi). The project budget was approximately 5 million euros (M€).

The first step of this project was the introduction of a co-innovation model (Figure 2) for aligning project stakeholders with the goal of accelerated digitalization. The model was operationalized around the 'Grand Challenges' (GCs) based on industry needs in a triple helix setting. The GCs were data-driven supply chain and production, robotics fusion and labour in the digital work environment. Each stakeholder in the triple helix was assigned specific roles and responsibilities.

- Factories provided a platform for co-innovation by opening actual production environments for proof-of-concept trials (PoCs). The PoCs were rapid (typically lasting 3–6 months) experiments or pilot projects that aimed to demonstrate that the developed solution was feasible for practical application. The factories co-led the GCs, proposed development topics and created PoCs together with researchers and SMEs. Successful solutions were scaled up within the factory and scaled out to factory networks utilizing existing pipelines.
- SMEs offered digitalization services and products to factories via subcontracting, with the aim of providing a sustainable service business and products.
- Research institutions co-led GC teams, facilitated ecosystem-level co-operation, carried out research in PoCs, provided assistance with business model creation and SME scouting, and educated future employees via university courses and supervision of master's and PhD theses.
- The public funder was responsible for the provision of government support through funding, and thus, lowering the risk associated with testing new technologies.

< Insert Figure 2 here >

The operationalization of the innovation model began with the identification of real-life factory needs. To address those needs, factory personnel, researchers and SMEs co-created possible solutions for the problem. Their ideas were implemented at the factory as a PoC through real-life trials of the technology and its economic viability. Learnings from each PoC were shared openly from factory to factory, and this allowed for their quick adoption. Following this, the best solutions were commercialized by SMEs and disseminated to Reboot's partner global factory networks with the help of the scale-up process; thus, the benefits were unleashed for the companies. Experience sharing with companies and factories outside Reboot (second-wave factories, as depicted in Figure 2) allowed them to follow and deploy solutions that had been tested and approved by Reboot factories.

The operationalization of the co-innovation model resided on four main attributes or enablers: adaptivity, experience sharing, SME co-innovation and scale up. Adaptivity involves the selection of development topics based on changing factory needs and progress in digitalization. This attribute helped to identify common GCs and to ensure the further development of PoCs. With experience sharing, it was possible to further validate the PoCs and establish a culture of experimentation for carrying out digitalization experiments and implementing a digitalization strategy, as experience sharing allowed for learning and testing a wide range of digitalization solutions with low risk. SME co-innovation was introduced to implement and productize the developed PoCs in individual factories, as well as for other partners in the ecosystem. Finally, from the viewpoint of creating a business impact, the scale-up process made it possible to disseminate successful solutions to several factories, thus improving return-of-investment considerably.

4. Results

4.1 Project results

The project selected for the case study, the Reboot IoT Factory project, was large in scale and was entrusted the unique task of creating and further developing a co-innovation model that can be applied to other industrial domains and projects, and thus, have a wide impact on society. Along with enhancing the broader societal impact, the core aim of the project was to facilitate a digital transformation in the manufacturing industry. The collaboration patterns were designed so that each triple helix stakeholder had a specified role and take-away experiences in the innovation ecosystem; in this way, the highly complex stakeholder responsibilities and their engagement were successfully managed. This approach also provided university researchers with the opportunity to learn about the real-life needs of factories and to obtain real-life data from production. This enabled scientists to shift their innovation towards industrial needs and develop their vertical understanding, thus increasing the relevance of their results. For industrial factories, the latest state-of-the-art technologies proved to have an impact on productivity, as they were able to find many new SMEs for experience sharing and contact them and negotiate co-operation. An open structure of innovation and the inclusion of new applications in the ecosystem opened the doors for small companies without a direct means to discussion with large players. As a result, new SMEs became part of the ecosystem, and several SMEs even had the opportunity to commercialize their business by expanding production from one factory to several. With regard to the funder’s role, Business Finland was mainly involved in the project as a funding provider, as an external evaluator and a steering member, but was not directly involved in the creation of technology solutions.

< Insert Table 1 here >

With regard to practical implementations, rapidly addressing the emerging research needs in a dynamic way, identifying grand challenges in real time, fast trial of PoCs and further scale up were considered to be the most important aspects of co-innovation and value-creation. Furthermore, the ecosystem approach enabled trust, strong co-operation and a common aim across the companies and research partners.

The results of the project can be summarized as follows: digital acceleration through the implementation of 20 PoCs, significant improvements in generating new revenue and references from large corporations, and greater insight into successful cross-ecosystem disseminations and co-innovation model implementation.

4.2 Survey results

The success of the project collaboration was measured with the help of a self-administered questionnaire that was sent to 116 project participants in the autumn of 2019. A total of 33 responses were received from industry partners (n = 11), research partners (n = 16) and SME partners (n = 6). The results of the survey are summarized in Appendix 1.

Overall, the collaboration success received a rather high score from the participants. This can be seen as an indication that the respondents felt that the operation model used in the project was successful in fostering collaboration and innovation. The limited number of respondents per group poses challenges for between-group comparisons, but the responses still indicate that the researchers agree most strongly about the questions related to regular communication and collaboration. The SME respondents scored the questions related to alignment and co-operation very highly. The results also show that they have a high level of perceived trust with regard to the sharing of the needed information within the ecosystem. Further, the responses also indicate that the participants are more than satisfied with the overall coordination and communication within the project. Additionally, the results show that the participants consider their goals to be very well aligned within the ecosystem, and they have all the relevant resources in terms of knowledge, information and technologies available to complete the tasks in the collaboration.

The survey also included two open-ended questions on collaboration and the project in general. Some relevant quotes from the answers provided by the representatives are presented below, along with the respondents' affiliation (F = Factory, R = Research, S = SME). The first question posed was 'How would your organization collaborate with other organizations in Reboot, if there were no project funding-related rules/limitations?'

Based on their answers, it seems that the respondents perceived the underlying guidelines and funding rules of the project to be significant and unique for collaborative innovation within the ecosystem. These were some of the responses:

'Much more limited cooperation. One-to-one interaction mostly' (F4)

'(…) there would be very little collaboration without project rules (…) it would be just another project where everyone does their own thing.' (R3)

The second question asked for general feedback: 'Do you have any other feedback about the Reboot project?'

The respondents demonstrated a high level of commitment and involvement with the project. In addition, various ways for SME involvement were proposed, and these will prove useful for the implementation of Phase 2 of the project.

'SME definition should be re-visited (turnover limit too low) as this limit greatly the potential of companies (…)' (F6)

'(…) I feel it was still very much easier to collaborate and communicate with the companies than it has been in any of my other projects.' (R4)

'(…) Smaller companies like us usually don't get a chance to work with bigger industry companies.' (S1)

5. Discussion

Industry 4.0 provides an essential platform for knowledge-sharing and co-evolving (Etzkowitz and Zhou, 2018; Reischauer, 2018) and can be leveraged in an ecosystem as a means for the participants to pursue their digital strategies. A triple helix approach promotes boundary spanning (Champenois and Etzkowitz, 2018), which allows participants to access knowledge and resources that are otherwise unavailable to them. Through an analysis of the results of the case study, a set of potential enablers of successful value co-creation process and co-innovation in an Industry 4.0 triple helix innovation ecosystem can be proposed as a key contribution of our study that is relevant for both researchers and practitioners. Figure 3 illustrates these enablers, which are positioned in the context of the literature review of this study that is presented in Figure 1.

< Insert Figure 3 here >

Industry 4.0 has enormous potential to change the entire value-creation system in the manufacturing industry (Birkel et al., 2018). As a means of realizing this potential, 'adaptivity' is considered as an aligning feature that allows the ecosystems to develop rapid solutions for the changing industrial and digital landscape. For example, throughout the studied project, work was planned and implemented in agile sprints. Each sprint lasted for approximately three months and concluded with a 'sprint review'. These reviews played a key role from the adaptivity perspective, as they brought the stakeholders together in one of the participating factories to network, review the progress of GCs (which were the main work packages of the project) and PoCs (experiments that combined research and factory digitalization) and plan further. On the one hand, adaptivity aligns contemporary business models with the value network and, on the other hand, it provides a shared platform for the partners so that they can co-create value and enable the ecosystem to be profitable and sustainable. Thus, the adaptivity element identified in our study contributes to addressing an important research and practical challenge, which is the goal alignment of partners; a potential risk identified in many earlier studies (Ghanbari et al., 2017; Dellermann et al.,

2017). Furthermore, the PoC structure that was analysed in our study represents a platform that advocates for sustained identification of innovation sources among ecosystem actors and further enables continuous improvement in the infrastructure, which has been identified to be a success factor in earlier studies (Durst and Poutanen, 2013).

Mechanisms for both collaboration interaction and joint knowledge creation, sharing and transfer are essential for value co-creation process (MacGregor and Carleton, 2012). As a related contribution, one of our study's findings was that that understanding the significance of new ways of value creation through knowledge flow requires active experience sharing. As digitalization culminates in a series of experiments that each involve significant technological, process and economical changes, it is crucial that the experiences and best practices from these experiments are shared. In our case study, we identified and demonstrated a practical way to implement this principle for the benefit of all the partners in the ecosystems in terms of collaboration, commercialization and value co-creation. For example, in order to co-innovate, one factory acts as an innovation platform for each PoC, while other factories can follow its progress and plan the adoption of the solution. Further, research organizations identify and allocate suitable resources for each PoC, and the PoCs allow researchers to move from laboratories to a real-life factory context and to familiarize themselves with the settings where PoC solutions will be deployed. These findings are practical examples of triple helix type of boundary spanning (Champenois and Etzkowitz, 2018) that is conducive to brainstorming about the solution creation and deployment and the factory's market needs.

As the studied case shows, triple helix actors created, shared and transferred knowledge through manifold experience-sharing activities. For instance, tech reviews were a series of online lectures where presenters from research organizations, SMEs and/or factories tried to increase awareness and co-operation between project participants. Publications, theses, blogs, fairs and innovation scouting were other ways the participants used to communicate scientific findings from the project to larger audiences and to raise interest in research co-operation, global dissemination and state-of-the-art mapping. Further, regular meetings were also organized by the project administration. Our findings show that this type of activities can help in the development of mutual trust, commitment and effective ways of communication, and lead to the development of collaborative capabilities, supporting earlier studies (e.g., Blomqvist and Levy, 2006).

Collaborative capabilities are particularly important in the context of this study, as they relate to both project collaboration (Camarinha-Matos et al., 2017) and to the adoption of digital innovations (Liao et al., 2017). The key capabilities for effective collaboration and value co-creation include trust, communication and commitment (Blomqvist and Levy, 2006). As one contribution, our study illustrates a practical example where high levels of trust within the project ecosystem can allow for the sharing of both successes and failures related to IoT technologies and associated practices, and factories could avoid several pitfalls through this empirical knowledge. This is supported by our findings from the survey, which showed a high level of trust, coordination and effective communication between the triple helix participants that were involved in co-creating a collaborative environment for joint value (Morgan and Hunt, 1994).

Besides the role of SMEs in larger parts of economies, they are usually overlooked because they do not have enough monetary resources to grasp the opportunities, in contrast to larger enterprises (Müller et al., 2018; Musa and Dabo, 2016; Piccarozzi et al., 2018). A potential solution for SMEs is networks and alliances and participation in the innovation ecosystem (Müller et al., 2018). From the point of view of the Reboot project, inclusion of the SMEs in triple helix innovation and SME co-innovation helped factories in leveraging the PoC solutions for their benefit, as well as the benefit of other partners in the ecosystem. Engaging SMEs earlier on and including them in a tighter way in the co-innovation process speeded up implementation of the production and allowed SMEs to consider playing a leading role when scaling up the PoC. To overcome the limitation of SMEs with regard to their slower pace in embarking on digital transformation identified by Müller et al., (2018), our case study shows that larger companies can provide the resources for the SMEs to co-innovate, gain confidence in the business and grow their own businesses.

In order to boost digital innovations to a larger scale, further scale up is required. Scaling up can help companies in bringing the PoC solutions to other factories, as well as to other project partners in the ecosystem, and can also help SMEs develop commercial solutions. In particular, the long-term benefits to SMEs are crucial for the health of the ecosystem, and reinforce the cycle presented in Figure 3 by encouraging further disruption and innovation.

6. Conclusion

This study focused on value co-creation in innovation ecosystems through triple helix collaboration in the Industry 4.0 context. The case study was the Finnish publicly funded project Reboot IoT Factory, which involved close collaboration between manufacturing companies, research institutions and SMEs. The first part of this study included an analysis to assess existing patterns of triple helix collaboration for value co-creation in the Industry 4.0 environment. The analyses showed that value creation based on triple helix collaborations require collaborative capabilities in the innovation ecosystem. Furthermore, strong interdependencies and the composition of actors based on a common goal and no direct competition made boundary spanning in the ecosystem easy and workable. Thus, the composition of actors and effective management are important with regard to avoiding conflicts and power issues in such projects.

In the second part of the study, four enabling factors for the successful implementation of Industry 4.0 triple helix collaboration were identified, namely, adaptivity, experience sharing, SME co-innovation and scale up. The results indicated that the co-innovation model based on experience sharing can accelerate digitalization of the Finnish manufacturing industry. They also demonstrated that research projects can be conducted in a dynamic way to address quickly emerging research needs, implement fast trials and scale up the solutions that have been developed. Yet, this type of operation requires adoption of the ecosystem approach with mutual trust, intensive collaboration, and the identification of common aims among the project participants. The results presented in Section 4 demonstrate a novel, experimental operating model that has the potential to meet the goal of effective collaboration, and it also describes the collaborative capabilities required to co-create value in the innovation ecosystem.

The present findings enrich our understanding of the good practices required to create innovation systems. The study provides both theoretical and practical contributions that were discussed in detail in section 5. As prior industrial revolutions built upon replacing old machines with new ones, Industry 4.0 relies on production of data through sensing, creating value from this data through analytics, automating routine non-value-adding tasks and moving human employees to tasks of higher productivity. Furthermore, business models are increasingly based on delivery of complete digitalization solutions as services. The collaborative innovation model presented in this study aims towards continuous skill development for individuals, unrestricted access to learning and transformation from a traditional work to a knowledge work and then to a learning worker. The findings also provide further insight into collaboration patterns and capabilities within an Industry 4.0 triple helix ecosystem. Practitioners can follow our illustration of the enabling factors to understand how to position their organisations as actors in the innovation ecosystem and to develop a practical strategy for collaborative innovation and value creation. Our findings can also be useful for large businesses to create useful engagement strategies for SMEs to become a part of innovation ecosystems. Moreover, we provide insights for decision makers so that they can focus on certain enablers based on their ecosystem requirements.

It should be noted that the findings are qualitative and are based on a single case; therefore, the generalizability of the findings are limited. However, replications of the Reboot model in different contexts could further refine the results presented in this study. Furthermore, Finland is a one of the most highly developed countries in the world with a tradition of technological advancement, and this provides a unique co-creation space for the implementation of the triple helix as a boundary-spanning format. As Kimatu (2016) has pointed out, there is great disparity among countries with regard to the implementation of the triple helix model. The national context should, therefore, be considered when extrapolating the results.

We did not look outside of the triple helix, e.g. the quadruple helix and quintuple helix, which includes societal (Carayannis and Campbell, 2009) and environmental factors (Carayannis et al., 2012). Therefore, further research could focus on how taking small steps towards generating knowledge societies can emerge and lead to green economies (Carayannis et al., 2012). Moreover, since the focus of this study was mainly on organizations as whole, future studies should focus on more individualistic view moving from knowledge societies to learning workers. Integrating these perspectives in future research could provide a more holistic view of collaboration, innovation and value co-creation in Industry 4.0 ecosystems.

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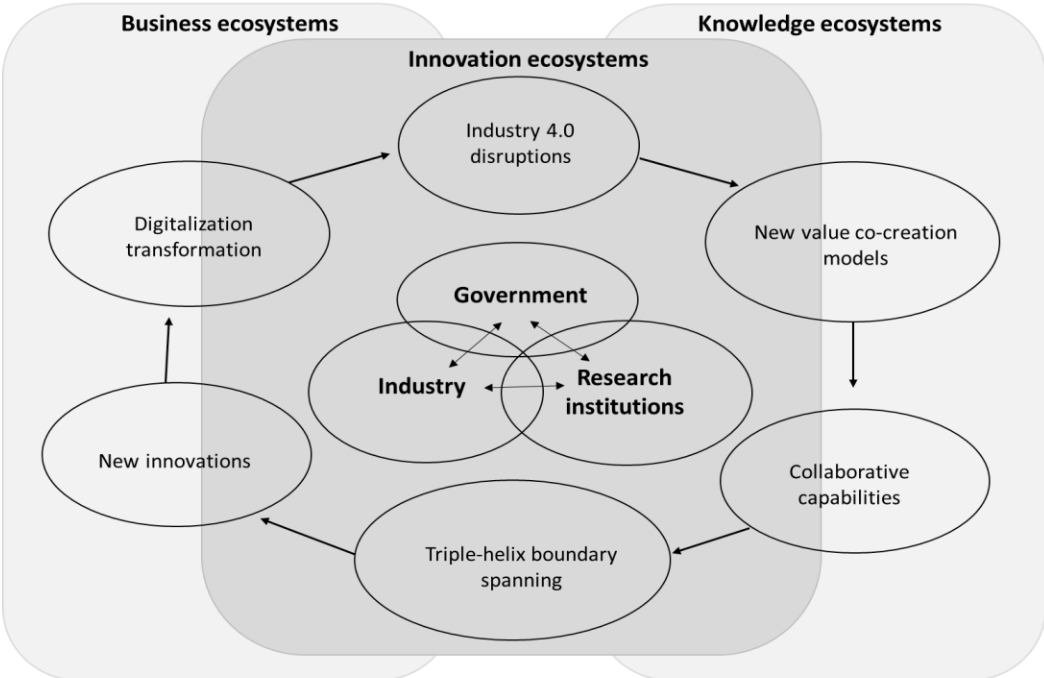

Figure 1 *Value co-creation, collaborative capabilities and triple helix collaboration in the dynamic transformation of Industry 4.0 innovation ecosystems*

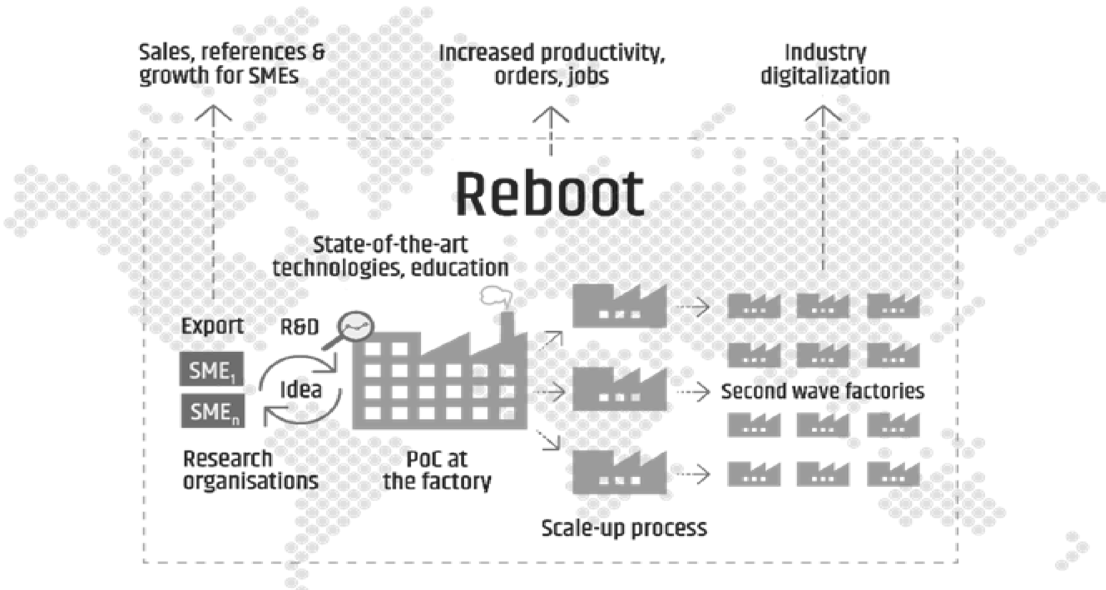

Figure 2 *Illustration of the Reboot innovation model*

Title

***Table 1** Key results of Reboot Phase I*

Working years	2018-2019
Industry domain	Manufacturing
Companies (Industry)	ABB, GE Healthcare, Kongsberg Maritime, Nokia and Ponsse
Research institutions (University)	VTT Research Institute of Finland, University of Oulu and Åbo Akademi
Funding body (Government)	Business Finland (external evaluator with no direct involvement in the technology solutions)
Complexity (stakeholder/task)	High level of complexity
Structured innovation process	Open structure (inclusion of new applications in the ecosystem and a high level of commercialization)
Approach to Industry 4.0 innovation	Solving grand challenges: • Data-driven supply chain and production • Robotics fusion • Labour in the digital work environment
Examples of proof-of-concepts to solve grand challenges	○ Value of services enabled by digital solutions ○ Use of mobile robots in material handling ○ Gamification on the factory floor
Critical success factors for innovation	✓ Adaptivity ✓ Experience sharing ✓ Scale up ✓ SME co-innovation
Achievements in terms of innovation	• Successful development and implementation of the co-innovation model • Purchase of services worth 0.8 M€ from 32 SMEs • 20 PoCs at the factory stage, 3 PoCs at the commercialization stage
Achievements in terms of triple helix innovation	❖ Trust created: addition of 4 more partners to the consortium ❖ IoT research exploring the industrial domain: 200+ researchers visited the factories ❖ Cross-ecosystem dissemination: 1000+ participants were part of the experience-sharing activities

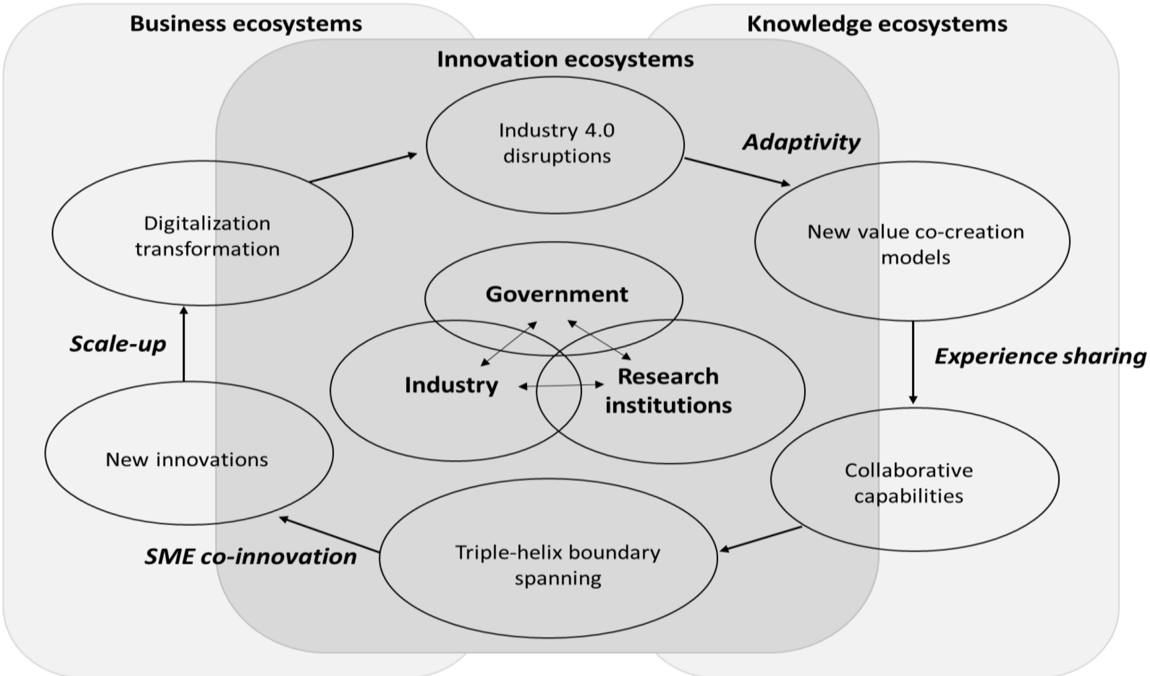

Figure 3 *Enablers for value co-creation in an Industry 4.0 triple helix innovation ecosystem*

Appendix 1. Survey results (1 = strongly disagree, 5 = strongly agree)

Question	Affiliation	N	1	2	3	4	5
Reboot project members “swim or sink” together.							
	All	33	1	3	13	13	3
	Factory	11		2	3	6	
	Research	16	1	1	7	6	1
	SME	6			3	1	2
Reboot project members want each other to succeed.							
	All	33			3	20	10
	Factory	11			1	8	2
	Research	16			1	9	6
	SME	6			1	3	2
The goals of Reboot project members are aligned.							
	All	33		3	6	20	4
	Factory	11		2	3	5	1
	Research	16		1	3	10	2
	SME	6				5	1
Reboot project members structure things in ways that favour their own goals rather than the goals of other project members.							
	All	33		13	6	14	
	Factory	11		5	2	4	
	Research	16		5	3	8	
	SME	6		3	1	2	
Reboot project members have a “win-lose” relationship.							
	All	33	9	17	6	1	
	Factory	11	2	6	3		
	Research	16	6	7	2	1	
	SME	6	1	4	1		
Reboot project members like to show that they are superior to each other.							
	All	33	8	17	3	3	2
	Factory	11	2	8	1		
	Research	16	5	7	1	1	2
	SME	6	1	2	1	2	
Reboot project members’ goals are incompatible with each other.							
	All	33	7	18	5	3	
	Factory	11	2	5	3	1	
	Research	16	5	9		2	
	SME	6		4	2		
I have information and help from project members in order to do my task well.							
	All	33		1	5	13	14
	Factory	11		1	3	4	3
	Research	16				6	10
	SME	6			2	3	1

I have to work together and consult with project members to do my task well.							
	All	33	1	4	10	13	5
	Factory	11	1	2	4	4	
	Research	16			5	6	5
	SME	6		2	1	3	
I have to meet regularly with Reboot project members to communicate about work-related matters.							
	All	33		9	7	12	5
	Factory	11		4	3	4	
	Research	16		3	2	6	5
	SME	6		2	2	2	
Project participants consider the nature of the tasks, individual resources, and fields of expertise when they negotiate about task division.							
	All	33		3	9	20	1
	Factory	11		2	4	5	
	Research	16		1	4	10	1
	SME	6			1	5	
Project members discuss about sharing regular routine tasks, including taking meeting minutes, scheduling next meeting, saving notes, and writing weekly progress reports.							
	All	33		8	14	10	1
	Factory	11		5	2	4	
	Research	16		3	9	3	1
	SME	6			3	3	
Key resources such as knowledge, technologies and competencies are readily available to the SMEs.							
	All	33		6	10	13	4
	Factory	11		2	3	5	1
	Research	16		3	6	5	2
	SME	6		1	1	3	1
Key resources such as knowledge, technologies and competencies are under factory partners' control.							
	All	33		10	13	10	
	Factory	11		1	7	3	
	Research	16		6	6	4	
	SME	6		3		3	
Key resources such as knowledge, technologies and competencies are already “installed” as part of the project’s asset base.							
	All	33	1	4	15	13	
	Factory	11		3	5	3	
	Research	16	1		9	6	
	SME	6		1	1	4	