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TOWARD A BETTER UNDERSTANDING OF COLLABORATIVE RESEARCH, DEVELOPMENT, AND INNOVATION (R&D&I) — EXPLORING VIRTUAL, PHYSICAL, AND COGNITIVE STRUCTURES

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Abstract

Objective of the study: The research in this paper contributes to the understanding of how physical, virtual, and cognitive structures support innovation ecosystems' multi-actor research, development, and innovation (R&D&I) collaboration in its different phases.
Methodology/Approach: The research's methodological approach is based on a qualitative case study research strategy. It is done by exploring three innovation ecosystem cases. The case data comprises the case ecosystems' existing documentation that was supplemented with five semi-structured interviews.
Originality/Relevance: Based on the findings of this research, it was possible to explore how industry and academy partners are collaborating through virtual, physical, and cognitive structures. Our cases also provide empirical evidence on how physical industrial sites can be used as environments for collaborative industry-academy R&D&I work.
Main Results: As a result, the paper presents lessons learned from three different innovation ecosystem cases that involve industrial, technology, and academy partners to tackle industrial use cases through virtual, physical, and cognitive structures. An example of such lessons learned is assembling dynamic teams to solve industrial problems.
Theoretical/Methodological Contributions: This article builds an understanding of how virtual, physical, and cognitive structures support collaboration between different participants in their joint R&D&I work covering industry-academy collaboration. The article also explains practical examples of this using innovation ecosystem cases.
Management/Social Contributions: The findings of this study may benefit professionals and managers who have an interest in understanding collaborative R&D&I and how physical, virtual, and cognitive structures can support it. Furthermore, the results provide means and experiences for innovation ecosystem managers to facilitate the definition of operational models suitable for the context of their innovation ecosystems.

Keywords: Innovation, Industry-Academy collaboration, Innovation ecosystem, Collaboration structures

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CONTRIBUTOS PARA UM MELHOR ENTENDIMENTO DA INVESTIGAÇÃO, DESENVOLVIMENTO E INOVAÇÃO COLABORATIVOS (I&D&I) – EXPLORANDO AS ESTRUTURAS VIRTUAIS, FÍSICAS E COGNITIVAS

Resumo

Objectivo do estudo: A investigação apresentada neste artigo contribui para a compreensão de como as estruturas físicas, virtuais e cognitivas servem de apoio à colaboração entre múltiplos actores envolvidos nas diferentes etapas de investigação, desenvolvimento e inovação (I+D+I), no contexto de ecossistemas de inovação.
Metodologia Enfoque: A metodologia de investigação baseia-se numa estratégia de estudo de caso qualitativo. A investigação é realizada explorando três casos de ecossistemas de inovação. Os dados do estudo de caso incluem documentação referente aos ecossistemas, complementada com recurso a cinco entrevistas semiestruturadas.
Originalidade/ Relevância: Com base nos resultados do estudo, é possível explorar de que forma parceiros industriais e investigadores colaboram através de estruturas virtuais, físicas e cognitivas. Os casos analisados fornecem evidência empírica acerca de como sítios industriais físicos podem ser usados como contextos para o desenvolvimento de trabalho colaborativo I+D+I entre a indústria e a investigação.
Resultados Principais: Como resultados, o artigo apresenta lições aprendidas a partir de três casos distintos de ecossistemas de inovação envolvendo parceiros industriais, tecnológicos e de investigação envolvidos em casos de uso industriais, através de estruturas virtuais, físicas e cognitivas. Um exemplo das lições aprendidas refere-se à constituição de equipas dinâmicas para a resolução de problemas industriais.
Contributos Teóricos/ Metodológicos: O artigo expande o entendimento acerca de como estruturas virtuais, físicas e cognitivas servem de apoio à colaboração entre diferentes participantes, enquanto desenvolvem trabalho I+D+I no contexto de colaboração entre indústria e investigação. O artigo também fornece e explica exemplos práticos, fazendo uso de casos de ecossistemas de inovação.
Contributos para a Gestão Sociedade: Os resultados do estudo contribuem para as práticas de profissionais e gestores com interesse em compreender trabalho colaborativo I+D+I, e em particular de que forma as estruturas físicas, virtuais e cognitivas podem apoiar esse trabalho. Os resultados contribuem ainda meios e experiências que os gestores de ecossistemas de inovação podem mobilizar para a definição de modelos operacionais adequados ao trabalho colaborativo em ecossistemas de inovação.

Palavras-chave: Inovação, Colaboração indústria-investigação, Ecossistema de inovação, Estruturas para colaboração.

CONTRIBUCIONES A UNA MEJOR COMPRENSIÓN DE LA INVESTIGACIÓN, EL DESARROLLO Y LA INNOVACIÓN (I&D&I) COLABORATIVOS – EXPLORACIÓN DE ESTRUCTURAS VIRTUALES, FÍSICAS Y COGNITIVAS

Resumen

Objetivo del estudio: La investigación de este artículo contribuye a comprender cómo las estructuras físicas, virtuales y cognitivas apoyan la colaboración multiactor en investigación, desarrollo e innovación (I+D+i) de los ecosistemas de innovación en sus diferentes etapas.
Metodología/Enfoque: El enfoque metodológico de la investigación se basa en una estrategia de investigación cualitativa de estudio de casos. Esta investigación se realiza explorando tres casos de ecosistemas de innovación. Los datos del caso comprenden la documentación existente de los ecosistemas de cada caso que se complementó con cinco entrevistas semiestructuradas.
Originalidad/relevancia: Con base en los hallazgos de esta investigación, fue posible explorar cómo la industria y los socios de investigación están colaborando a través de estructuras virtuales, físicas y cognitivas. Nuestros casos también proporcionan evidencia empírica sobre cómo los sitios industriales

físicos pueden usarse como entornos para el trabajo colaborativo de I+D+i entre la industria y la investigación.
Resultados principales: Como resultado, el documento presenta lecciones aprendidas de tres casos diferentes de ecosistemas de innovación que involucran socios industriales, tecnológicos y de investigación para abordar casos de uso industrial a través de estructuras virtuales, físicas y cognitivas. Un ejemplo de tales lecciones aprendidas es ensamblar equipos dinámicos para resolver problemas industriales.
Contribuciones teóricas/metodológicas: Este artículo desarrolla la comprensión de cómo las estructuras virtuales, físicas y cognitivas apoyan la colaboración entre los diferentes participantes en su trabajo conjunto de I+D+i que abarca la colaboración entre la industria y la investigación. El artículo también explica ejemplos prácticos de esto utilizando casos de ecosistemas de innovación.
Gestión/Contribuciones Sociales: Los hallazgos de este estudio pueden beneficiar a los profesionales y gerentes que tengan interés en entender la I+D+i colaborativa y cómo las estructuras físicas, virtuales y cognitivas pueden apoyarla. Además, los resultados proporcionan medios y experiencias para que los gestores de ecosistemas de innovación faciliten la definición de modelos operativos adecuados para el contexto de sus ecosistemas de innovación.

Palabras Claves: Innovación, Colaboración industria-investigación, Ecosistema de innovación, Estructuras de colaboración.

1 INTRODUCTION

Collaboration between different actors is a necessity for successful innovation (Bogers, Zobel, Afuah, Almirall, Brunswicker, & Dahlander, 2017; Lee, Olson, & Trimi, 2012; Miller, McAdam, & McAdam, 2018). This progress is in line with the emergence and development of "open" innovation models (Chesbrough & Garman, 2009), where the focus of open innovation is broadening from company-centered approaches to emphasizing deeper collaboration with external actors (Dahlander, Gann, & Wallin, 2021). In other words, external knowledge sources are not seen as either substitutes or complementary to internal Research, Development, and Innovation (R&D&I). Instead, collaborative innovation is emphasized to be a necessity (Lee et al., 2012; Dahlander et al., 2021) and building knowledge-based capabilities for competitive advantage (Robertson, Caruana, & Ferreira, 2023).

Managing the continuation of research, development, and innovation, from the exploration of new knowledge to the commercialization of innovation in a collaborative setting, is not an easy task. Collaborative research, development, and innovation (R&D&I) work is particularly challenging, as it requires the coordination of a variety of actors. The participants' interests and roles may change during the process, affecting their motivation and interest in participating in collaborative R&D&I activities (Paasi, Valkokari, & Rantala, 2013; Valkokari, 2015; Oh, Phillips, Park, & Lee, 2016). Thus, research is still scarce on appropriate structures in which multiple actors collaborate in an R&D&I process that changes over time (Leminen, Nyström, & Westerlund, 2020; Simeone, Secundo, & Schiuma, 2017; McAdam & Debackere, 2018; Miller et al., 2018; Hannah & Eisenhardt, 2018). There is a limited understanding of interaction practices that enable collaborative R&D&I (Bürger & Fiates, 2021; Faccin, Balestrin, Martins, & Bitencourt, 2019). Therefore, more research is needed on the dynamics of arrangements for collaborative R&D&I, i.e., i) research (R) for problem setting and knowledge creation, ii) development (D) through pilots and demonstrations for the diffusion of knowledge, and iii) innovation (I) referring here, especially to knowledge exploitation for business.

The purpose of this paper is to build an understanding of how virtual, physical, and cognitive structures support collaborative R&D&I work. This will be done by analyzing three different innovation ecosystem cases. Innovation ecosystems are introduced as integrating mechanisms between the exploration of new knowledge and its exploitation for value co-creation in business (Ketonen-Oksi & Valkokari, 2019; Ritala & Almpanopoulou, 2017). Following Adner's (2016) ecosystem-as-structure perspective and related definition of "ecosystem" as an *alignment structure* of a multilateral set of partners that need to interact, we focus on studying how different *physical, virtual, and cognitive structures* bring actors together and enhance collaboration. Furthermore, our cases provide empirical evidence on how physical industrial sites can be at the core of collaborative R&D&I work where industry, technology partners, and academies together solve practical industrial problems connected to the everyday life of workers and build new businesses based on these novel solutions. Operation in this setting stresses the importance of fruitful collaboration between industrial, technology, and academy partners. Therefore, we compose the research question as follows: how do virtual, physical, and cognitive structures support collaboration between different participants in different phases of R&D&I work?

This paper is organized as follows. First, we compiled the related research and defined the basis for the research need. Then, the research methodology, cases, and methods used for data collection and analysis are introduced. Section 4 then presents the results of the study, and Section 5 discusses the results and summarizes the lessons learned.

2 RELATED RESEARCH

Collaborative R&D&I processes are highly situated and contingent (Pavitt, 2005) with linkages among actors, organizations, and the different network settings between them. All actors in a multi-actor setting need to collaborate in formal and informal networks not only to explore and exploit new knowledge but also to create and shape supportive practices strategically. The actors come and work together through different virtual, physical, and cognitive structures, where the industrial sites and practical problems connected to the everyday life of workers are the starting point and driving force of the collaborative R&D&I processes. Industrial sites can be seen as the core of collaborative R&D&I (Khan, Kauppila, Iancu, Jurmu, Jurvansuu, Pirttikangas, Lilius, Koho, Marjakangas, & Majava, 2022). Therefore, our empirical evidence describes how different industrial sites function as the core of collaborative R&D&I and how collaboration around this kind of environment is arranged and supported.

2.1 From open to collaborative innovation

Understanding actors' resource contributions within dynamic, interdependent multi-actor settings is crucial for collaborative R&D&I. According to the open innovation literature, one of the main pitfalls of this can be the mismatch between the solutions proposed by experts and the capabilities of the companies to implement such solutions (Vanhaverbeke, Chesbrough, & West, 2014; Enkel, Gassmann, & Chesbrough, 2009). Thereby, the need to integrate cross-sectoral collaboration in the early stages of the innovation process is emphasized (e.g., Gassmann, Enkel, & Chesbrough, 2010; Bullinger, Neyer, Rass, & Moeslein 2010; Dahlander et al., 2021). However, it is not yet clear how firms can do so from a process perspective (Simeone et al., 2017). Thus, innovation ecosystems have recently been mentioned as a suitable mechanism to integrate a variety of actors into joint problem-solving (Ketonen-Oksi & Valkokari, 2019). In this study, innovation ecosystems are defined as "dynamic and co-productive settings for collaborative R&D&I activities that are characterized by a high level of interdependence and co-evolution of value between the industry and research-based ecosystem actors" (Jacobides, Cennamo, & Gawer, 2018; Ketonen-Oksi & Valkokari, 2019). Innovation ecosystems bring together and integrate two main components: 1) the exploration of new knowledge for innovation and 2) their exploitation through commercialization (Valkokari, 2015; Oh et al., 2016). However, the management of dispersed knowledge is crucial for ecosystems' success (de Vasconcelos Gomes, de Faria, Borini, Chaparro, dos Santos, & Gurgel Amaral, 2021a), and interaction practices that enable collaborative R&D&I are needed (Bürger & Fiates, 2021; Faccin et al., 2019).

The collaboration of industry and academia has been studied widely. The previous research already provides knowledge related to the collaboration of industry and academia in the form of lessons learned, best practices, models, challenges, and recommendations (e.g., Valkokari, Valkokari, Rantala, & Nyblom, 2021; Garousi, Shepherd, & Herkiloglu, 2020a; Garousi et al., 2020b; Runeson & Minör, 2014; Marijan & Gotlieb, 2021). For instance, Valkokari et al. (2021) studied four case studies of industry-academia collaboration and reported the best practices, weaknesses, and strengths of three collaborative innovation mechanisms. Garousi et al. (2020a) present industry-academia collaboration experiences and lessons learned based on 26 projects. Furthermore, they provide recommendations to practitioners, helping establish collaboration between industry and academia. They also present five maturity levels of closeness between industry and academia. Runeson & Minör (2014) present a model that can be used to characterize industry-academic collaboration projects from the perspectives of time, space, activity, domain, and scenario. They also provide a case demonstrating the model. The model highlights a dualistic view of benefits, immediate benefits, and more far-reaching research for the industry. Sandberg et al. (2011) present the results of a study of an eight-year experience with a Collaborative Practice Research (CPR) effort between a telecommunications company and an academic research institute. The article states ten factors for successful projects and ten action principles to help set up industry-academic collaboration. However, there may also be problems in cooperation or issues that hinder collaboration. Based on a literature review, Garousi et al. (2020b) identify the root causes of the low relevance and utility of research. The leading causes are (1) Researchers having simplistic views (or wrong assumptions) about SE (Software Engineering) in practice, (2) Lack of connection with industry, and (3) Wrong identification of research problems. Thus, choosing a research topic is challenging and requires time and trust between partners (Misirli, Erdogmus, Juristo, & Dieste, 2014). There might also be a lack of interest and commitment to collaboration from the industry or research side (Marijan & Gotlieb, 2020). The recent COVID-19 pandemic has also set challenges to industry-academia collaboration, and it has been studied, e.g., by Rioux & Kajikawa (2020).

2.2. The process of collaborative R&D&I work

Previous literature offers various and contradictory definitions of processes (Leminen et al., 2020). Here, we follow the definition of Van de Ven (1992) and study a process as "a sequence of events or activities that describes how things change over time, or that represents an underlying pattern of cognitive transitions by an entity in dealing with an issue." Here, joint R&D&I activities are based on the knowledge needs of working life (i.e., solving practical industrial problems connected to the everyday life of workers). We approach knowledge creation (Nonaka & Takeuchi, 1995) and organizational learning (Crossan, Lane, & White, 1999) as interconnected and complementary activities without going into a detailed discussion of their theoretical roots (for that purpose, see, for instance, Brix (2017)). The collective R&D&I process within an innovation ecosystem creates knowledge that is usable either by academia and education or industrial practitioners, usually in the form of new practices or upgraded solutions, as well as longer-term research knowledge (Valkokari et al., 2021).

Knowledge creation, distribution, and learning occur through interaction, and this is crucial for ecosystems' success (de Vasconcelos Gomes et al. 2021a). Hence, the structure through which a variety of actors interact influences the collective sense-making knowledge conversion (Nonaka & Krogh, 2009) and, thereby, the scope of diffusion. Thus, knowledge creation within the R&D&I environment typically involves different participants representing, e.g., industry, academia, and financing (Khan et al., 2022). Although the collaboration between researchers and practitioners has been discussed widely in literature, current literature offers a limited view on knowledge co-production within ecosystems (de Vasconcelos Gomes et al., 2021a). Specifically, there is a need to have a longitudinal view of all the phases of knowledge creation and distribution from research to the commercialization of innovation (in line with innovation ecosystems' primary purpose of integrating exploitation and exploration). For instance, Marijan and Gotlieb (2021) have reported a model for industry-academia collaboration (called Certus), where industry and academy representatives form a joint team to solve an industrial problem and its related research problem using a series of steps. Similarly, we have identified three main steps within industry-academy collaboration as follows: i) research, which aims at the creation of new practice-oriented knowledge (fundamentally different from traditional basic research done in the university sector); ii) development, which focuses on testing and demonstrating the use of knowledge created; and iii) innovation, which refers to the commercialization of this knowledge. This is the first dimension of our conceptual framework presented in 2.4.

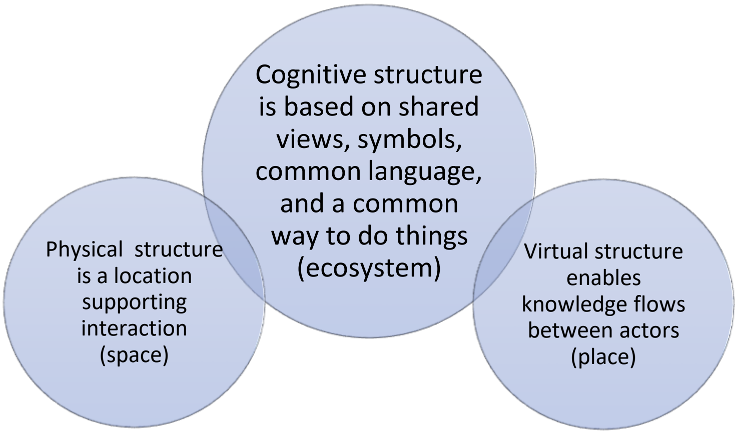
2.3 Collaboration structures for a multi-actor R&D&I process

The collaborative R&D&I process in ecosystems consists of collective actions (Thomas & Ritala, 2022), i.e., repetitive sequences of cooperation, conflict, and compromise (Pellikka & Ali-Vehmas, 2016; Adner, 2016; Leminen et al., 2020; Carayannis, Grigoroudis, Campbell, Meissner, & Stamati, 2018). Thereby, alignment refers to the mutual agreement that aims to balance the interdependencies between actors and their activities (Adner, 2016). The roles of players and collaboration structures are not stratified in advance but instead are reorganized and negotiated at each phase of joint R&D&I (Etzkowitz & Ledesdroff, 2000). During the collaborative R&D&I process, several *physical, virtual, and cognitive structures* can encourage a variety of actors to work together, i.e., enabling the shared knowledge creation process required (Peschl & Fundneider, 2012) by enabling dynamics between actors' positions and knowledge flows.

All three collaboration structures have their own part in enabling collaborative R&D&I processes (Figure 1). This division of three alignment structures (physical, virtual, and cognitive) is based on the well-known Japanese concept of Knowledge Ba, which refers to a shared space for emerging knowledge flows and relationships, and the space itself can be physical, virtual, or mental (Nonaka & Konno, 1998). Similarly, social movement theory identifies three interrelated factors that make up collective actions: an opportunity structure consisting of the opportunities and constraints fronting the movement, a mobilizing structure that comprises the formal and informal ways of organizing and framing processes that lead to the generation of shared meanings (Davis & McAdam, 2000; Thomas & Ritala, 2022). Thus, the previous literature often explores one of these three elements separately. Furthermore, the previous literature has indicated that knowledge flows are often bidirectional in nature, which is in contrast with the identified need for more broad co-creational engagements (Arnkil, Järvensivu, Koski, & Piirainen, 2010).

Figure 1

The virtual, physical, and cognitive structures for collaborative R&D&I



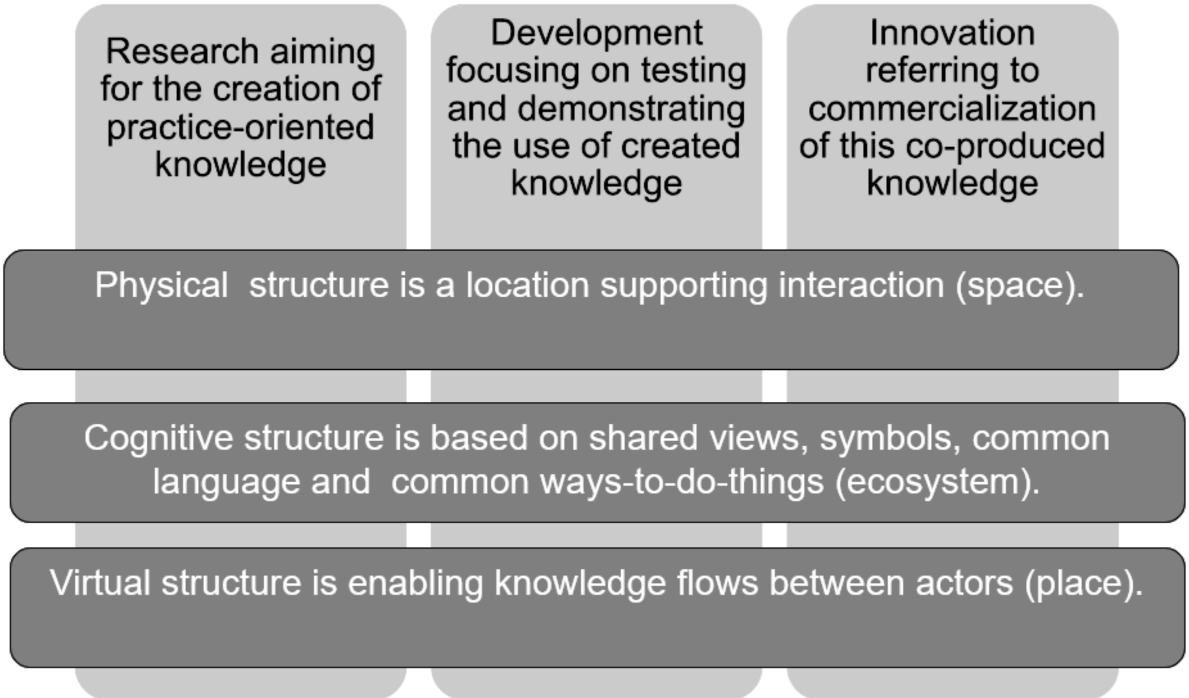
The physical structure brings actors together and enables interaction, whereas the virtual structure supports knowledge flows between them. Firms have already, for a while, been paying increasing attention to the physical environments in which creative and innovative activities take place (Moultrie, Nilsson, Dissel, Haner, Janssen, & Van der Lugt, 2007). Thus, the previous literature on the impacts of physical structures has mainly focused on how the creativeness of individuals can be enhanced (Oksanen & Ståhle, 2013) or how different innovation hubs and living labs empower serendipity of encounters within open innovation processes. Within networked R&D&I, enabling knowledge flows (i.e., building Knowledge Ba) between actors is crucial for the continuation of the process (Valkokari, Paasi, & Rantala 2012), and different virtual structures (like virtual meeting platforms) have a critical enabling role. Finally, the cognitive structure is considered to be the third enabler of knowledge sharing and creation (Clark, 2008), which is necessary for collaborative innovation. Knowledge management scholars have especially highlighted the importance of cognitive capabilities (de Vasconcelos Gomes, Lopez-Vega, & Facin, 2021b) in learning and knowledge creation. Cognition is about anticipating the need for action and developing the capacity to predict the outcome of those actions; it is closely linked to the framing processes that lead to the generation of shared meanings (Davis & McAdam, 2000). Through a sense-making process, this cognitive structure is created through shared experiences and views, as well as a common language and identity of an ecosystem. Peverelli (2000) has introduced the concept of organization theory, defining two elements of a cognitive structure: the social element, the actors involved, and the cognitive element, their shared cognitive matter (shared views, symbols, common language use, common ways to do things, etc.). In this study, we use the concept of cognitive structure with the broader meaning of an interconnected system of actors and their activities, including the shared view on the outcome of those actions across industry-academy borders.

2.4. Our conceptual framework

In order to guide the empirical research and analyses, we have developed a conceptual framework bridging together the identified three phases of collaborative innovation and three alignment structures of innovation ecosystems (Figure 2). Although there is rich literature on open and collaborative innovation, a deeper understanding of interaction practices that enable collaborative R&D&I is needed (Bürger & Fiates, 2021; Faccin et al., 2019). Our conceptual framework aims to bridge this gap and provide supporting views on knowledge management within ecosystems (de Vasconcelos Gomes et al., 2021a).

Figure 2

The conceptual framework of virtual, physical, and cognitive structures for collaborative R&D&I



This supports the identification of appropriate processes and structures in which multiple actors collaborate and is at the core of our contribution to the discussion of collaborative R&D&I settings that change over time (Leminen et al., 2020; Simeone et al., 2017; McAdam & Debackere, 2018; Miller et al., 2018; Hannah & Eisenhardt, 2018).

3 RESEARCH DESIGN

The goal of this study is to shed light on how shared virtual, physical, and cognitive structures support the R&D&I process in a multi-actor setting. The research question is as follows: how do virtual, physical, and cognitive structures support collaboration between different participants in different phases of joint R&D&I work? This research is done by exploring three innovation ecosystem cases, one of the unique features of which was that they all occurred during the COVID-19 period. We follow the structure presented in (de Vasconcelos Gomes, Facin, Leal, de Senzi Zancul, Salerno, & Borini, 2022) to organize the research design section.

The research methodological approach is based on a qualitative case study research strategy. Since the topic is not widely researched, a case study approach with an abductive approach was selected (Dubois & Gadde, 2002).

3.1 Data collection

The innovation ecosystem cases were selected based on their suitability for studying the research question, availability to researchers (access to cases), and the fact that they represent different industries (Table 1). The authors were also active members in these ecosystems, and thus, they have a deep prior understanding of how the ecosystems work. However, it can be argued that authors were affected by ecosystems' inside experiences. Furthermore, all the innovation ecosystem cases are from the same country. The first case, innovation ecosystem "A," offers an open innovation marketplace to link the challenges of the Finnish forest industry to the innovative offerings of Finnish IT (Information Technology) companies. The second case, innovation ecosystem "B," develops a business ecosystem and an experimentation digital platform to promote the development of intelligent data-based services in the context of smart buildings. The third innovation ecosystem case, "C," connects Finnish manufacturing factories, academic institutes, and SME (Small and Medium-Sized) companies in agile co-creation and experience sharing in real-world production environments. All of these cases targeted the involvement of innovative solution provider companies (typically start-ups or SMEs), industrial companies, and academy partners together to solve the use cases set by industrial partners. Therefore, the cases provide good ground to study multi-actor R&D&I activity. In this setting, industrial partners (i.e., use case companies, core partners, and factories) provided use cases. SMEs (i.e., solvers, developers, and catalysts) built PoC solutions to solve the use cases. The operation of the innovation ecosystems is organized into projects funded by national funding authors.

Table 1

Case descriptions

Characteristics	Case A	Case B	Case C
Domain	Forest industry	Smart buildings	Manufacturing industry
Purpose	A business-driven innovation marketplace for the forest industry, its Finnish vendors, and the digital sector to learn and innovate together to be leaders on a global scale.	An innovation undertaking that creates a high-performing and dynamic ecosystem that defines the future of the built environment.	An innovation ecosystem that manages technology proof-of-concepts, focusing on production among the ecosystem partners and has an extensive experience-sharing program—Phase 2 project.
Implementation focus	Innovative digital solution proof-of-concepts for the forest industry	Intelligent service proof-of-concepts for smart buildings	Digital solution proof-of-concepts for more efficient production
Ecosystem type	Innovation ecosystem	Digital platform-based innovation ecosystem	Innovation ecosystem
# of partners	22 companies + 3 academic organizations	6 companies + 1 academic organization	8 companies + 4 academic organizations
# of participating companies	12 large companies, 9 SMEs	8 SMEs	49 SMEs
Partner types	Use case companies, Solvers, Catalyzers, Research, Funding	Core partners, Developers, Research, Funding	Factories, Solvers, Research, Funding
Coordinator (orchestrator)	Academy partner	Academy partner with strong core partners' guidance	Academy partner

The target of all case ecosystems was to enable multi-actor R&D&I work. In order to understand how shared structures could support this multi-actor R&D&I process, the operational models of the case ecosystems needed to be understood in detail. Therefore, the case data comprises the case ecosystems' existing documentation that was supplemented with five semi-structured interviews (Table 2). The existing documentation was collected with the innovation ecosystems' project managers. The ecosystems' operational model was described in different documents. These documents varied from project plans to other documents such as ecosystem playbooks, ways of working documents, etc. These documents were read first to understand the concepts and operational models of the ecosystems. Five semi-structured interviews were used to deepen understanding of case data. The intention was to complement the understanding of the operational models of the ecosystems. In addition, in the interviews, it was investigated how collaboration practices (e.g., meetings, teams, events, tools, workshops (WS), co-development environments) were implemented in practice at different phases of the R&D&I process and what kind of experiences the interviewees had concerning the collaboration. A unique feature was that during all the case projects, the restrictions related to COVID-19 began, which had an impact on how collaboration could take place.

Table 2

Case data sources

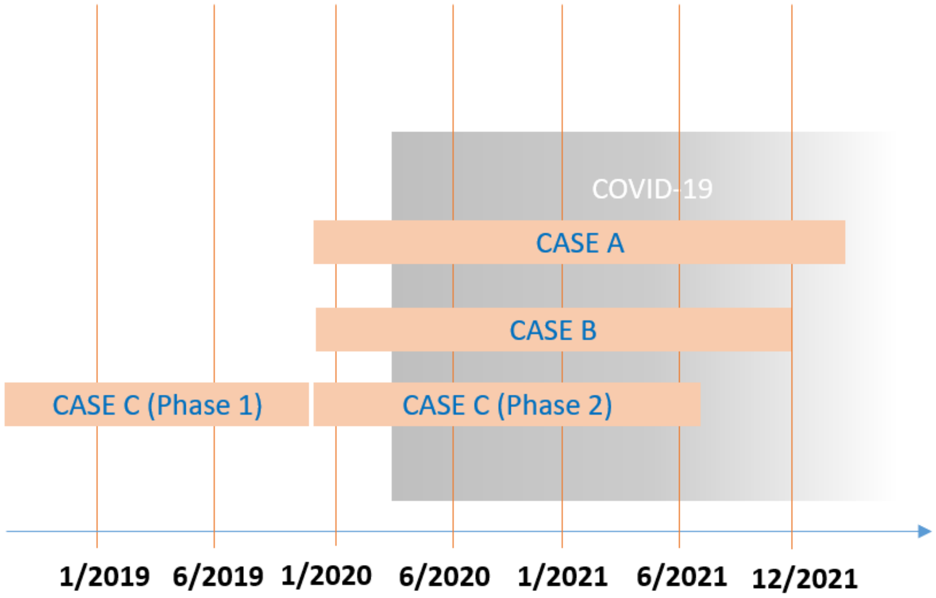
Case	Documents	Role of interviewees
Case A	Playbook document (PowerPoint presentation: 65 slides) Agreements (Word documents: Consortium agreement (34 pages), Use case NDA template [7 pages]) Project plan (Word document: 50 pages)	Innovation ecosystem project leader Innovation ecosystem work package leader
Case B	Vision and way of working document (PowerPoint presentation: 13 slides) Agreements (Word documents: Consortium agreement (15 pages) with attachment: Experimentation Platform Data Processing Agreement (6 pages); Demo Space Rental agreement [19 pages]) SME engagement model document (PowerPoint presentation: 45 slides) Consortium Project Plan (Word document: 50 pages)	Innovation ecosystem project leader
Case C	Governance plan (Word document: 11 pages) Agreements (Word documents: Consortium agreement [31 pages]) Project plan (Word document: 85 pages)	Innovation ecosystem project leader Innovation ecosystem SME and scale-up coordinator

The ecosystems have described their operational model in various documents. These documents describe, for instance, ecosystem values, roles, and responsibilities, how to join an ecosystem, agreements, development process models, coordination practices, communication, and collaboration events. Common to all ecosystems is that ecosystem decision-making and the monitoring of progress happened using a steering board and other boards (e.g., Case A Core group and Case B Project management team). The decisions and boundaries set by these boards formed a playground for the ecosystems' daily operation. All the ecosystems had a coordinator role (orchestrator) that coordinated and engaged the daily operation of the ecosystem according to the boundaries set by the steering board and other boards. In all ecosystems, the academy partner acted as coordinator. However, in Case B, the core partners influenced the activities of the coordinator, because the coordinator was subcontracted by the core partners.

The fundamental characteristic of the operational model of all ecosystems is that they were developing innovative Proof-of-Concept (PoC) solutions for real-life industrial problems. Therefore, the practical development model was participative in all cases. It involved industrial companies (Case A "use case companies;" Case B "core partners;" Case C "factories"), technology companies (Case A "solvers;" Case B "developers;" Case C "solvers"), and academy partners together to build and test PoCs as well as share experiences for industrially based problems in an industrial environment (e.g., in Case B at the construction company's physical building and construction site). However, each ecosystem cases had its own detailed collaboration practices regarding how they have engaged the operation around industrial environments (described in the innovation ecosystem's operational model). Furthermore, the COVID-19 era (period of COVID restrictions in Finland) had its own influence on collaboration in the ecosystems (Figure 3). Case C represents a case that has a longer history. "Phase 1" was the first project that started the ecosystem operation (Khan et al., 2022), and "Phase 2" was a successive project that continued the operation of the ecosystem with a new funding frame. In this paper, Case C focuses on Phase 2.

Figure 3

Timespan of the case ecosystems



3.2 Data analysis

For qualitative data analysis, we used content analysis (Burnard, Gill, Steward, Treasure, & Chadwick, 2008) with the preliminary frame defined in the previous section. Our analysis is abductive (Dubois & Gadde, 2002) in nature. The phenomenon under consideration in the research and the research question is connected to the already existing and previously studied research topic and the conceptual frame based on it. This framework creates a structure for the reality that the empirical material of our research examines. Thus, an already existing theory is not directly tested; instead, the aim is to find new insight and understanding of the subject in question. The case data was first coded and organized using process steps (R&D&I). Then, more specific collaboration practices were identified from the data at each step. The actors of each process phase were identified, and the structures (virtual, physical, cognitive) were mapped to the collaboration practices.

The challenges and "what worked well" related to the multi-actor R&D&I collaboration were extracted from interview data. Two main themes have emerged from the case data, namely "industrial environment for collaborative work" and "the use of multi-actor joint teams," which were highlighted by the interviewees of all cases. These emerging themes led us to include the industry-academy collaboration literature in the study. Furthermore, the impacts of COVID-19 have emerged from the data.

Triangulation was used to increase the quality of the research. Case ecosystems' existing documentation was used as primary data that was supplemented with five one-hour semi-structured interviews as secondary data. Interviews were used to discuss and supplement ecosystem practices by verifying the information presented in the documents as well as to add information that was missing. Therefore, the interviews were used as a way to understand better the data and reduce information bias. Furthermore, the case data was analyzed by one researcher, and a research colleague reviewed the results of the analysis. The results were also reviewed by the interviewees, who represented different case ecosystems. This increased the quality of the analysis.

4 RESULTS

This research aims to understand how shared virtual, physical, and cognitive structures support the R&D&I process in a multi-actor setting. We will consider how multi-actor collaborative R&D&I is supported by virtual, physical, and cognitive structures in the ecosystem cases. Furthermore, the effects of COVID-19 on the ecosystem cases will be considered since it characterized the operating environment of the ecosystem cases during their lifetime.

4.1 Virtual, physical, and cognitive structures supporting collaboration in the R&D&I process

In this section, we identify how shared virtual, physical, and cognitive structures were used to support multi-actor collaborative R&D&I work. Playbooks, ecosystem operational models, and agreements contribute to the cognitive structures since they intend to build common understanding and rules for the whole ecosystem—a kind of mental setting for operation in the ecosystem. Based on these boundaries and guidelines, each use case team defines its own hands-on approach to how to operate, such as ways of working, common language, and shared goals that are gradually built in the interactions between the actors.

Next, we present an analysis of how the collaborative R&D&I work was carried out in each case. We use the steps defined in the related research chapter (research, development, innovation). The innovation phase contains activities that relate to adopting PoCs to industry (into a new factory of the same industrial partner or to a new partner [called Scale-Up here]) and commercialization activities. Furthermore, we divide the analysis into activities, the role of industry site and joint teams, and describe which physical and virtual structures were used to support the collaboration in each step.

Table 3

Analysis of Case A R&D&I work (I = Industry; T = technology company; R = Research) (P = Physical; V = Virtual)

	Research: research & practical problem	Development: engaging third parties, co-development, and experience sharing	Innovation: scale-up and commercialization
Activities	Insight: - Communication of predefined industrial use cases (I&R&T) ○ Joint use case-specific WSs for all ecosystem members interested in the use case in question (P) - Problem framing (R&I&T): ○ Industrial partner and use case-specific interviews (V) and WSs (V) Technology research (R)	Vision setting (T&I&R): - Vision WSs (V) Engagement (I&T&R): - Batch reviews (Bazaar) (P, V) Concept development (T&I&R): - PoC/MVP development meetings/sprints (V) Experience sharing (I&T&R): - Batch reviews (P, V) Meeting Squares (V) Longer-term research (R&I&T) - WSs and interviews related to research beyond the PoC (V)	Commercialization actions beyond the PoCs (T)
Role of industry site	Factories as the source of detailed needs/problems (P)	Factories as PoC test environments (P)	
Joint teams	Formation of joint use case teams	Update of joint use case teams Ecosystem's joint effort	1-to-1 collaboration of ecosystem partners

In Case A (Table 3), the ecosystem used predefined industrial use cases as a base for R&D&I collaboration. The use cases came from industrial partners and reflected their practical problems in factories, and they were seeking digital solutions to tackle them. Each use case went through the same process of Insight-Vision-Concept phases. The formation of a joint use case team started with an F2F workshop where the use case owner (industrial partner) introduced the use case. Then, academy partners and other industrial partners expressed their interest in joining the use case team. The use case owner (industrial partner) was responsible for nominating the use case team partners. Detailed problem framing during the insight phase was led by an academy partner of the joint use case team, and work was done in collaboration with the industrial partner (use case-specific events). This was done first by identifying relevant industrial stakeholders (employees working in factories) who were selected for interviews and asking them to participate in the workshops to formulate and understand the practical industrial problem to be solved. This helped the academy partners to discuss problems and understand them more deeply. The academy partners made state-of-the-art technological studies related to industrial problems to understand the potential research problem and technology solutions for the identified industrial problem and find potential technology providers from the innovation ecosystem to the use case. The research and industrial problems were related. The industrial problems were practical for which mature technology was known to exist. The research problems indicated more far-reaching targets where industrial problems were seen as a subset of research problems and short-term first-step solutions toward the long-term research target.

Vision workshops were used to define the long-term solution vision (that relates to the research problem) and the short-term solution vision that would be the first step toward the long-term solution vision. Potential additional technology partners (typically SME companies) were invited to pitch their offerings in a Batch review for forest industry use case companies. Furthermore, there were separate sessions in the Batch review where potential new technology partners could have use case-specific informal discussions with use case companies (so-called "Bazaar"). We found that SME-size technology partners are very agile and looking for well-defined problems and a straightforward process on how to proceed. This is understandable due to their limited resources. In the Case A innovation ecosystem, the work package leader stated that it is more challenging to involve SME-size technology partners in the research phase. Therefore, they should primarily be involved in discussing possible solution concepts during the beginning of the development phase once the industrial problems have already been identified. PoC development happened using agile sprints with academy partners observing and collecting experiences. Academy partners led the research track, and industry and technology partners were used as a source of information to define research-based solution concepts and test them (e.g., interviews were primarily used to verify solution concepts with use case industrial and technology partners). The PoC development and testing process was rapid, and the research track took a longer time to continue its work after PoC. The factories of the use case industrial partner worked as a ground for all activities done by the use case team (source of needs/problems, development phase cooperation between factory staff and technology companies, PoC test environment). The experiences of the PoC development and long-term research concepts were shared with other ecosystem members iteratively in Batch reviews and Meeting squares (regular virtual meetings of the whole ecosystem). Technology partners did the commercialization of the solutions beyond the PoCs. When the project started, the intention was to have mainly physical meetings, workshops, and events. However, COVID-19 caused problems with this and forced the case ecosystem to use virtual events.

Table 4

Analysis of Case B R&D&I work (I = Industry; T = Technology company; R = Research) (P = Physical; V = Virtual)

	Research: research & practical problem	Development: engaging third parties, co-development, and experience sharing	Innovation: scale-up and commercialization
Activities	UX workshops for defining use cases (I&R): - UX workshops resulting in use case backlog (P) - Prioritization WS for the use case backlog (V) Building the experimentation platform ecosystem vision and research problem (R&I): - State-of-the-art research (academic and practical viewpoints) (V) - Platform ecosystem WS (P) - External consultant facilitated vision WS (P) 1-to-1 F2F discussions between an academy partner and an industrial partner. (P)	Engagement (I&T): - Challenge competitions facilitated by third-party facilitator companies (P, V) Development (I&T&R): - Epic/PoC meetings (V) - Experimentation platform and developer portal (V) - Slack for developer communication (V) Experience sharing (I&T&R): - Weekly status meeting (V)	Business possibilities (I&R): - Foresight WSs (V) - Business WSs (V) - Go-to-market WSs (V) 1-to-1 joint offering discussions (I&T) Longer-term research (R&I&T) - WSs and interviews related to the platform emergence and business models (V)
Role of industry site	Buildings and their users as the source of needs/use cases (P)	- Demonstration space at the start-up campus to demonstrate PoCs (P) - Buildings and construction sites as PoC (platforms) environments (P)	
Joint teams	Ecosystem's joint effort Formation of use case teams	Update of joint use case teams Ecosystem's joint effort	1-to-1 collaboration of ecosystem partners Ecosystem's joint effort

In Case B (Table 4), the use cases of real users and employees of the buildings and construction sites were clarified at the beginning of the project in joint face-to-face (F2F) user experience (UX) workshops with ecosystem partners. Academy partners participated actively in this phase. Use cases were then prioritized in an ecosystem joint workshop (for the first set of PoCs). Based on prioritized use cases PoC teams were formed comprising industrial and academy partners. Academy partners conducted 1-to-1 F2F discussions with each industrial partner to enable academy partners to understand use cases and their context better and map them to research ideas. Furthermore, the whole ecosystem formed a platform ecosystem vision and agreed on the research problem for the ecosystem's research track. Industrial partners led PoC teams.

Technology partners (SME companies to solve industrial problems) were asked to participate in the process by using challenge competitions to study prioritized use cases and find innovative solution concepts for them. In challenge competitions, the ecosystem announces the competition on its website and markets the competition in different media. SMEs that were interested in the topic sent a "one-pager" to the ecosystem explaining how they would solve the industrial use case. Based on the material received, the ecosystem selected several SMEs to present their solution proposals at mentoring meetings held to introduce the experimentation platform to the SMEs and iterate the solution proposals jointly. Finally, these proposals were presented to the ecosystem. The ecosystem then decided which solution providers continued to the PoC phase (joining the use case team). The use case teams implemented PoCs in physical buildings, construction sites, and common demonstration space (facilities rented from start-up campus) to demonstrate the functionality of the solutions. Academy partners participated actively in the experience collection phase. Since Case B represents a platform-based innovation ecosystem, it needed boundary resources to enable third-party application developers (SMEs) to build on top of the ecosystem's experimentation platform (SW platform). In practice, these comprised an open developer portal for externals with APIs, documentation, and tutorials, as well as Slack for developer communication. The ecosystem used weekly status meetings (whole ecosystem) for sharing PoC experiences in the ecosystem.

During the innovation phase, the ecosystem organized various joint workshops where all ecosystem partners jointly brainstormed what the commercial future of the Case B ecosystem would be. Close interaction and learning (PoCs) among the ecosystem partners resulted in tried-and-tested innovative joint offerings that could live and evolve further. These proceeded in 1-to-1 discussions toward commercialization. The cooperation of the companies in the ecosystem and use case teams facilitated the formation of these joint offerings. The companies were already getting to know each other and trusting each other. This would have been difficult to achieve without systematic practices and support from the ecosystem. The particular characteristic of Case B was that it looked at a start-up campus located in Helsinki as a collaborative physical space for the ecosystem. They found the start-up campus environment and facilities inspiring. Therefore, the steering group of Case B decided to rent a 300 m^2 demonstration room in spring 2020 from the start-up campus with a plan to equip it with a technical environment that would enable the demonstration and testing of smart building applications in a collaborative environment to which all ecosystem members have access. Unfortunately, COVID-19 forced the ecosystem to change the PoC building and demonstration plans.

Table 5

Analysis of Case C R&D&I work (I = Industry; T = Technology company; R = Research) (P = Physical; V = Virtual)

	Research: research & practical problem	Development: engaging third parties, co-development, and experience sharing	Innovation: scale-up and commercialization
Activities	Use cases based on industry needs (I) - Predefined when starting - New cases identified when the previous ones were solved Use case presentation and acceptance (I&R) - Industry presenting to each other and for research (P, V) - Discussion about what others have already done in the field that could help (P, V) Use case refinement (I&R) - Plans for implementation: discussions (P, V) - Detailed research plan and setting target: discussions (P, V)	Engagement (R&I&T): - Scale-up & SME team meetings (V) - SME workshops (V) Development (I&T&R): - PoC team meetings (V) Experience sharing (I&T&R): - Factory use case SME workshops (P, V) - Sprint reviews inside factory premises (P, V)	Common scale-up and commercialization (I&T&R): - Scale-up & SME team meetings (V) - Discussions with venture capitalists (P, V) Industry internal scale-up (I)
Role of industry site	Factories as a source of detailed needs/problems (P)	- Factories as PoC test environments (platforms) (P) - Research Institute laboratories (P) - Facilities of companies in the supply chain (P)	Other factories of industrial partners (P)
Joint teams	Ecosystem's joint effort Formation of joint use case teams	Update of joint use case teams Joint Scale-up and SME team Ecosystem's joint effort	Joint Scale-up and SME team 1-to-1 discussions with ecosystem partners and possible external partners

In Case C (Table 5), industrial partners provided predefined use cases as a base for R&D&I collaboration. The use cases were predefined by the industrial partners (under broader common industrial grand challenges) and reflected practical problems in factories to which they were seeking digital solutions. These use cases were discussed in joint meetings in the ecosystem. On the other hand, academy partners defined related far-reaching research problems to tackle as a parallel research track and allocated suitable resources for use cases (PoCs), therefore allowing researchers to step into a real-life industrial context (factories). Use cases were refined in 1-to-1 (industry-academy) physical F2F and virtual meetings. From the research point of view, the Case C project manager stated that when a researcher gets to visit the factory floor (physically) and discuss or interview workers and see the real industrial problems in their natural environment, their eyes open. This similar understanding of industrial problems and their context is difficult to achieve in any other way. Each use case went through the same PoC process. A PoC team containing industrial and academy partners was formed and led by an industrial partner.

In the engagement phase, potential technology partners (SME companies) were scouted (SME coordinator and SME workshops) to participate in the work of the ecosystem. The Scale-up and SME team led by the SME coordinator (academy partner) had the primary responsibility of enabling this. The factories of the industrial partners offered themselves as sandboxes to find business use cases and research and implement PoCs. They offered a real-world environment with professionals on the factory floor to tackle short-term problems. This cannot be obtained in the labs at universities or other research institutes. Being so close to the industry ensured that PoCs were relevant, and it tied the factory employees to the process as well as research to the real-life industrial context. This provided a better chance of continuation because of an already existing "shop floor" commitment. The research labs were used for more far-reaching research when more research infrastructure was needed than the environment of the final use provided. The operational model of Case C also led to joint solutions (several SMEs) where each SME focused on its specialty, and one of them operated as an integrator providing the integrated solution. The experiences of the PoCs and research were shared in events that were organized on factory premises. A joint Scale-up and SME team coordinated the PoC solution scale-up. There was a discussion about whether the PoCs merit scale-up and if there were interested factories of the industrial partners in the ecosystem who would like to adapt the PoC for themselves as well and proceed with that internally.

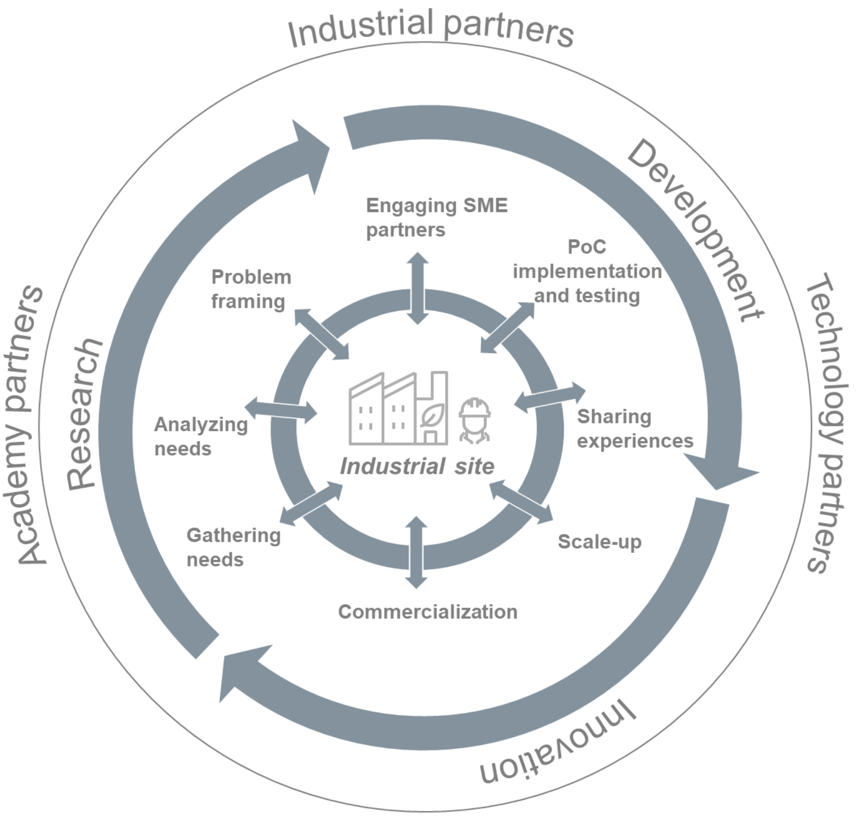
4.2 Common ground for R&D&I collaboration—physical industrial sites

At the heart of all the use cases have been physical industrial sites, in the context of which R&D&I work has been done in evolving joint teams containing industrial partners, technology partners, and academy partners (see Figure 4). The R&D&I process covered the whole period, from the formation of a problem relevant to both industry and research, co-development of the PoCs, to the broader adoption of the solution in the context of the target industrial company or commercialization. In each case, the ecosystem-specific operational models (playbooks, etc.) provided the joint teams with a common framework of practices that were applied to the R&D&I work using practices such as collaborative PoC process models with joint use case teams and shared events (Bazaar, Sprint reviews) with the rest of the ecosystem. The ecosystems provided systematic models for engaging new SME partners to solve industrial problems in industrial environments. In all cases, the academy partners had a key role at the beginning of the R&D&I process to understand the industrial needs and identify their relevance to the academic community (i.e., systematic long-term challenges that needed research to support industrial future strategic competitive-edge building beyond the short-term problems). The practical R&D&I collaboration happened at various physical and virtual events, such as workshops and meetings. During the R&D&I process, use case teams were an essential element of cognitive structures within the ecosystem. This covered a common understanding of the solution being developed and its context, common terminology, and ways of working based on a standard operating model of the ecosystem.

By combining the operating models of the three ecosystems from the perspective of industrial-based PoC development, the following steps can be identified during the R&D&I process that take place within the boundaries provided by the ecosystems (Figure 4). The research phase focuses on gathering and analyzing industrial needs, mapping them to the current research discussion, and, based on that work, framing the problems (both practical short-term and academic long-term problems). The development phase comprises systematic engagement of technology partners (SMEs) to solve industrial PoCs, as well as testing and experience sharing. In parallel with these processes, there is ongoing longer-term research where practical PoC development is seen as one step on a research pathway toward solving the more far-reaching problem. After the development in the innovation phase, PoC scale-up and commercialization take place, and research continues toward longer-term research problems that can generate new practical short-term PoC development cycles.

Figure 4

Industrial site as the core of R&D&I collaboration



During the R&D&I process, virtual, physical, and cognitive structures can help different actors work together. The three cases described in this article indicated that all of these structures support the operation, but the operational environment is not immutable. The innovation ecosystem also needs the capability to adapt its operational model based on changing situations. An example of this kind of situation was COVID-19, which forced the case ecosystems to change their settings and showed that the lack of physical structure can hamper interaction in some situations. For instance, in Case A, the ecosystem started to arrange events like Batch reviews as virtual meetings using the Teams communication platform supplemented with workshop tools (e.g., Miro). The move to virtual meetings hampered the informal discussions in Batch reviews (especially in Bazaar) between new potential technology partners and industrial use case companies. On the other hand, more formal communication of PoC experiences worked well in the virtual setting. The Case B consortium could not use a common experimentation facility on a start-up campus during COVID-19, causing PoC demos to be done only in the partners' facilities (buildings, construction sites). This limited the transparency of the demos for the whole ecosystem. In Case C, the new situation challenged the old way of keeping a sprint review at the factory, where a factory tour was arranged on the factory floor (presenting PoCs in practice). These events went virtual, but the physical factory tours were liked so much that virtual tours were planned for each hosting factory for everybody to see by remote video how production was arranged and how the PoCs were implemented. The virtual tour was a success as it can be replicated for other parties outside of Case C.

In Case C, some proofs-of-concepts could not go forward as planned because outsiders needed access to the factory floor, and those places were restricted to personnel only due to COVID-19. In some cases, factory personnel needed to conduct the proof-of-concept by themselves, with researchers only virtually participating in the PoC and analyzing the results afterward. This weakened cooperation between the academy and the industry. The SME and scale-up coordinator stated that a few of the PoCs even needed to be canceled as no suitable virtual or hybrid collaboration solution was found.

5 DISCUSSION

The research in this article contributes to the understanding of how physical, virtual, and cognitive structures support multi-actor R&D&I collaboration in its different phases. This research was done by exploring three innovation ecosystem cases, one of the special features of which was that they were affected by the COVID-19 period.

Enabling fluent collaboration and preventing the silo effect (Marijan & Gotlieb, 2020) between partners is essential since different organizations—industry, technology, and academy—are working together toward common goals. This can be achieved by providing a physical and virtual space for interaction between partners (Marijan & Gotlieb, 2020). In our ecosystem cases, this finding from previous studies was supported by joint use case teams that used various physical and virtual structures to enable collaboration. In the ecosystem cases, the operation of joint use case teams and ecosystem moved from physical events to virtual ones due to COVID-19, which caused some challenges. The effect of COVID-19 forcing the operational model toward a virtual one in industry-academia collaboration has also been treated by Rioux and Kajikawa (2020). They emphasize the use of facilitators in virtual events to encourage active participation. Our empirical cases showed that especially in the first phase of the collaborative R&D&I process, i.e., the research phase, it was important to start with physical events and F2F meetings to enable participants to get to know each other (i.e., build a cognitive structure between them) and, thereby, make it easier to move to virtual events due to COVID-19. Also, Misirli et al. (2014) report in their study that industrial partners favored smaller F2F meetings to discuss possible topics of interest in industry-academia collaboration. They also point out that building trust between partners takes time, which we also noticed during the research phase of collaborative R&D&I.

Joint multi-actor use case teams gathered industry, technology, and academy partners working together around problems relevant to both industry and academies. Similarly, Marijan and Gotlieb (2021) and Garousi et al. (2020a) proposed the use of joint industry-academia teams to solve industrial problems. Marijan and Gotlieb (2021) further state that teams do not have to be fully staffed from the beginning but refined based on competence needs. In our cases, the use case teams started with a combination of industry and academy partners (in the research phase), and that combination was then enriched with technology partners. Similarly, Marijan and Gotlieb (2020) stated that involving both sides early on in collaborative efforts mitigates a lack of interest and commitment from both the industry and academy sides.

The engagement of technology partners (primarily SMEs) at the beginning of the second phase, i.e., the development phase, happened in various ways. For instance, Case B used challenge competitions to engage technology partners in the joint use case teams solving industrial problems. On the other hand, Case A invited potential technology partners to discuss with industry partners (use case owners) in Batch reviews (Bazaar session), and new partners joined the use case team when applicable. However, this caused problems when these activities moved to the virtual setting instead of the physical one (COVID-19). Informal discussions (Bazaar sessions) that were needed for new partner entry to the operation of an ecosystem and the use case team were more difficult in the virtual environment. The strong involvement of technology partners (SME companies) at the beginning of the development phase to understand and solve industrial problems as part of the use case teams was important. In such a model of cooperation, large industrial companies provided their own industrial sites as a core for understanding the context of predefined industrial problems and finding solutions to them. SME companies were better able to understand the industrial context and trust that the problems to be solved had a commercial need and potential—this was indicated already in the first phase of Case C (Khan et al., 2022). For researchers, the industrial environment facilitated the understanding of industrial needs and their context and, therefore, enabled fruitful industry-academy cooperation and tackling problems of low relevance and utility of research (see, e.g., Garousi et al., 2020b).

Based on the empirical study, we have identified the critical tasks within the collaborative R&D&I process model (Figure 4). It has many similarities with the process model for collaborative Knowledge and Technology creation (Certus model) presented by Marijan and Gotlieb (2021)—the Certus model's problem scoping and knowledge conception maps to our model's research phase. Then, the Knowledge and Technology (K&T) development and transfer link to our model's development phase. However, our model also extends toward experience-sharing mechanisms between use cases in a collaborative development phase. Thus, this importance of experience and knowledge sharing is aligned with the social movement theory, highlighting the framing processes that lead to the generation of shared meanings (Davis & McAdam, 2000; Thomas & Ritala, 2022). In line with previous literature, these knowledge-based (Robertson et al., 2023) and cognitive (de Vasconcelos Gomes et al., 2021a) capabilities were identified as necessary for building future competitive advantages for involved actors. Finally, the third phase of our model, i.e., the innovation phase, emphasizes tasks similar to the K&T exploitation in the Certus model, i.e., organizational adaptation and market research. Thus, our focus was on the ecosystem level instead of an individual company, and the third phase of joint R&D&I was especially challenging at the ecosystem level as it required a change from innovation to business operations.

Our study highlighted that it was important that this collaborative R&D&I model started with active interaction between industry and the academy (meetings, workshops, and interviews to find the right practical and academic problems) and built a joint team with joint targets to solve—industrial needs and the academy's needs. This is also stressed by Garousi et al. (2020a) as well as Faccin et al. (2019). The joint use case teams gradually formed a common terminology, common ways of working, and common practical and research goals when working in the ecosystem. This formed a framework and common understanding for the use case team members to operate and understand what they wanted to achieve and, therefore, gradually formed the teams' cognitive structure as an interconnected system of actors and their activities across borders of industry-technology-academy partners. This could not be formed for the use case teams without the ecosystem-level common ground, i.e., playbooks and agreements, as well as discussion and learning from each other. Each team could fine-tune their internal practices and decide on using physical or virtual events, but how the teams worked at the ecosystem level was set and common in all use cases (e.g., sprint reviews, challenge competitions, Batch reviews). Then, in the innovation phase, there was a shift from the use case team level to individual industrial partners' internal activity and 1-to-1 discussions between industry and technology partners. Similarly, in the Certus model in solution adoption and pre-commercialization, the focus moves to the industrial lead team and the use of external resources (like business developers) (Marijan & Gotlieb, 2021).

If we look at the academic research problems and practical industrial problems defined in the ecosystem cases, we notice that they have different time spans. This is understandable as the industry is looking for immediate benefits while academy interests are beyond this (Garousi et al., 2020b). These findings are well in line with the time perspective of the model presented by Runeson and Minör (2014). They state that short-term cooperation is coordinated by consulting companies (in our cases, industry-driven) with mature technologies. The longer-term basic research work is coordinated by the academy, where a more thoughtful pace of academic processes is needed to complement the industry's higher speed. This might also include more immature technologies. In our cases, this meant that the longer-term research pathways were divided into shorter-term practical PoC steps for the industry.

Table 6 below is a summary of the lessons learned from the results concerning how physical, virtual, and cognitive structures supported the innovation ecosystem cases' multi-actor collaborative R&D&I work in its different phases. Based on the ecosystem cases, the cognitive structure of the ecosystem, and the use case, teams are built little by little through common concepts and goals, shared experiences, and working together. The cooperation varied depending on the stage of the R&D&I process. Academy partners played a substantial role in the research phase, while industrial and technology partners played a significant role in the development and innovation phase. During the life cycle of ecosystems, the situation of the surrounding world can also change. Therefore, operational agility is also a significant factor in R&D&I collaboration. COVID-19 forced cases to adapt to situations and find alternative forms of cooperation and ways of working. This was noticed in all cases during the life cycle of the cases.

Table 6

Lessons learned

Lessons learned	Physical	Virtual	Cognitive
Physical industrial environments (e.g., factories and construction sites) provide the operational context for understanding industrial problems and the development and testing of PoCs. These should be utilized already in the research phase as a vehicle to build a common understanding of the industrial problem and its context for the industry and the academy—this ensures that the subsequent activities go in the proper and fruitful direction in the development and innovation phases.	X		X
Start the research phase with physical F2F meetings/workshops to allow industry and research to understand each other and facilitate virtual meetings since different actors have, at this point, already met physically.	X		
The ecosystem's operational model has to be agile enough to allow use case teams to adapt to changing operational environment situations during the R&D&I process. COVID-19 is an excellent example of this— turning physical events into virtual ones (e.g., virtual factory tours instead of physical ones reported to be successful practice. On the other hand, informal discussions were hampered due to COVID-19 since physical events were not possible).	X	X	
Assemble use case teams around individual industry-based problems already in the research phase. These teams will evolve as new competence needs occur (e.g., new SMEs) during the development phase (i.e., they are dynamic). The use case teams build their cognitive structure little by little, where a multi-organizational team forms a common understanding of the solution being developed and researched, as well as builds common terminology and ways of working based on the ecosystem operating model.			X
The academic partner has a vital role in industrial and research problem setting in the research phase. The academic partner must step out of their comfort zone toward the industry, preferably visiting the factory floor and discussing the problems that need to be solved with the industrial employees.	X		X
Involve SME technology companies at the beginning of the development phase to solve identified industrial problems. SMEs need an existing industrial problem and context to understand how their offering could meet the problem and the requirements of the context. Use a straightforward, consistent approach/process supported by physical or virtual structures in the ecosystem to make SME partners participate in the operation of use case teams.	X	X	X
In the innovation phase of the R&D&I process, there was a shift from the use case team level to individual industrial partners' internal activity or 1-to-1 discussions between industry and technology partners. However, Case C also			X

coordinated this with a dedicated team to coordinate the scale-up of the solutions before 1-to-1 discussions or internal deployment of solutions. The formation of these 1-to-1 connections was facilitated by the cooperation of companies in the ecosystem during the research and development phases when the companies had already gotten to know and trust each other. Systematic ecosystem collaborative practices during previous R&D&I phases helped to achieve these 1-to-1 relationships in the innovation phase.			

6 CONCLUSIONS

The purpose of this article is to build an understanding of how virtual, physical, and cognitive structures support collaborative R&D&I work between different participants. This study was done by analyzing and presenting three innovation ecosystem cases as well as reporting lessons learned. When considering the case ecosystems as a whole, it can be noted that the well-defined playbooks/operational models enable common processes and experience sharing among the use case teams. The well-defined ecosystem-level practices and agreements allow fruitful cooperation between the parties during R&D&I work. All the use case teams operated according to the same ecosystem process, ensuring academy-industry collaboration and common goals, meaningful involvement of SMEs in joint development, and sharing experiences across PoCs so that the other ecosystem partners could learn from each other and understand other partners' capabilities and offerings.

The results of the present study cannot be interpreted without taking into account the study's limitations. Our study is based on three innovation ecosystem cases with ecosystem-specific collaborative settings. This naturally limits the generalizability of our findings, and more cases are needed to deepen the results. Furthermore, the number of interviewees was limited, and therefore, we may have a narrow picture of the situation of the case ecosystems. However, the authors played an active role in case ecosystems and, therefore, already have a deep understanding of their operation.

The findings of this study may benefit professionals and managers who have an interest in understanding collaborative R&D&I and how physical, virtual, and cognitive structures can support it. Furthermore, the results provide means and experiences for R&D&I managers to compare their operational environment with the environment of our cases and utilize the results to facilitate the definition of operational models suitable for the context of their collaborative R&D&I activities. Even if the results provide a body of knowledge on collaborative R&D&I in multi-actor settings, cross-sectoral studies in different contexts should be conducted to assess the generalizability of the results. This is essential for the continued advancement of the body of knowledge on industry-academia collaboration literature as well as emerging ecosystem studies. Furthermore, as the unit of analysis in our paper was the ecosystem, and we focused on R&D&I settings, we found the collaborative innovation literature more convenient than the actor-network or social network literature. However, both the Actor-Network Theory (ANT) and the Social Exchange Theory (SET) could provide an interesting avenue for future research, probably based on a single case study with a longitudinal approach in order to go deeper into the formation of cognitive structures between ecosystem participants.

The cognitive structure could be studied on different levels, from the ecosystem and organization to the individual's own cognitive space, which results in a unique categorization of their ideas, thoughts, and memories. The latest is an engrossing, although challenging research topic as the "mindset" of individuals is often mentioned as a critical enabler of collaborative R&D&I crossing organizational borders. Both of the perspectives mentioned above acknowledge the importance of innovation while simultaneously having a strong emphasis on sharing through collaboration.

AUTHORS' CONTRIBUTIONS

Contribution	Kääriäinen, Jukka	Valkokari, Katri	Siira, Erkki	Hemilä, Jukka	Jurvansuu, Marko
Contextualization	X	X	----	----	----
Methodology	X	X	----	----	----
Software	----	----	----	----	----
Validation	X	X	----	----	----
Formal analysis	X	X	----	----	----
Investigation	X	X	X	X	X
Resources	X	X	X	X	X
Data curation	X	X	X	X	X
Original	X	X	----	----	----
Revision and editing	X	X	X	X	X
Viewing	X	X	----	----	----
Supervision	----	X	----	----	----
Project management	X	----	----	----	----
Obtaining funding	X	----	----	X	----

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